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NUMERICAL ANALYSIS OF FLOW AND HEAT TRANSFER IN THE VAFB LOX STORAGE DEWAR TANK

By

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October 1984 CHAM/4040/6

Prepared For:

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Alabama 35812

Project Manager: J.H. Pratt
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PREFACE

This is the final report for the NASA Marshall Space Flight Center Contract No. NAS8-35666. The work has been performed at CHAM of North America, Incorporated, Huntsville, Alabama.

Technical discussions with and contributions of J. H. Pratt, A. L. Worlund and H. Aderhold of MSFC, and Laurence Keeton of CHAM NA are gratefully acknowledge.

ABSTRACT

The present report describes numerical simulation of three-dimensional transient distributions of velocity and temperature of liquid oxygen (LOX) in the LOX Dewar tank of Vandenberg Air Force Base (VAFB). LOX level gradually drops due to "Chilldown", "Drain Back", "Slow Fill", "Fast Fill", "Topping" and "Replenish" procedures. The present analyses cover the replenish time period only.

Four test cases have been considered. For all four cases, the input boundary conditions comprise of LOX facility heat loads, drain flow rates, recirculation flow rates and dewar heating. All the quantities are prescribed as functions of time. The first two test cases considered sensitivity of results to the computational grid. In Case 3, system heat load was changed, while in Case 4, a lower LOX level was specified.

Cases 1 and 2 showed that the temperatures were not sensitive to the grid refinement. This provided a basic check on the numerical model. Cases 3 and 4 showed that the thermal boundary layer motion near the tank surface becomes more significant at the late time, e.g. 5½ hours from replenish start. Comparison between results of Cases 3 and 4 showed, as expected, that the smaller initial LOX volume given in Case 4, results in higher temperature level. All calculated velocity and temperature distributions were found to be plausible.

Computations were performed with the aid of CHAM's general-purpose, finite-difference, flow-analysis computer code - "PHOENICS". This study demonstrated the feasibility and benefits of three-dimensional analysis of LOX flow and heat transfer within the Dewar.

Section 1
INTRODUCTION

BACKGROUND AND OBJECTIVE OF THE STUDY

The Space Shuttle External Tank (ET) LO_2 storage system at Vandenberg Air Force Base (VAFB) is smaller than at KSC, and thus it is expected to be more sensitive to heat loads. In the present study, attention is confined to the LO_2 Storage Dewar Tank of VAFB. During an ET loading operation, LO_2 (or LOX) level gradually drops due to the "Childown", "Drain Back", "Slow Fill", "Fast Fill", "Topping" and "Replenish" procedures. Figure 1-1 shows a schematic of the dewar tank and LOX levels at the end of these operations.

The temperature of LOX leaving the Dewar tank is a strong function of LOX facility heat loads, drain flow rates, recirculation flow rates and dewar heating. The present study is concerned with the LOX flow and heat transfer during the replenish period. The objective is to elucidate the flow and heat transfer details in the LOX Dewar. This information is useful in the analysis of overall system.

NATURE AND SCOPE OF THE STUDY

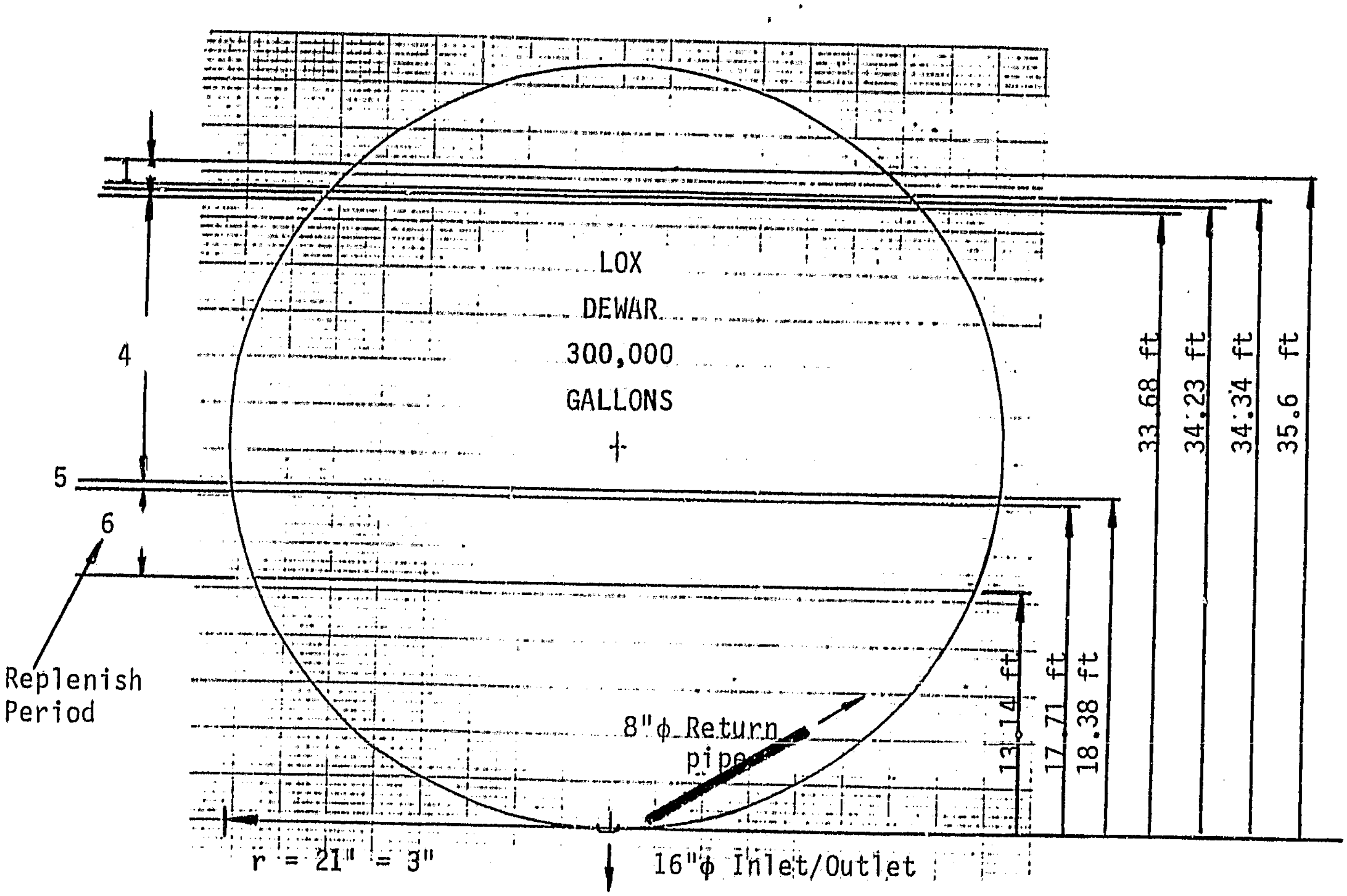
CHAM of North America Incorporated has performed computations and analysis of LOX flows with boundary conditions specified by the NASA Marshall Space Flight Center (MSFC). The study consisted of a total of four test cases.

Throughout the study, frequent discussions were held between MSFC and CHAM personnel. The results of each test case were presented in a meeting held at MSFC. Written discussions of results with graphical representations were also supplied in these meetings.

PURPOSE AND OUTLINE OF THE REPORT

The purpose of this report is to record the following:

1. Assumptions, mathematical basis and computational details of the numerical model;



Operating Procedure	Procedure Time	Total LOX Consumed (Gallons)	Total LOX Remains in Dewar after operating (Gallons)
0 Start Loading	0	0	279,000 (93 % LOX)
1 Chilldown	17 min	7780	271,220
2 Drain Back	10 min	725	270,495
3 Slow Fill	12 min	3710	266,785
4 Fast Fill	30 min	146,810	119,975
5 Topping	20 min	7000	112,975
6 Replenish	5.5 hrs	44,554.5	68,420.5

Figure 1-1. A Schematic Diagram of the Dewar Tank and LOX Levels During an ET Loading Operation.

2. Specifications of the test cases considered;

3. Computed results and observations; and

4. Conclusions and recommendations.

The report has been divided into four sections. The next section (Section 2) describes assumptions and mathematical basis. Specifications of the test cases, results and discussion are provided in Section 3. More detailed results viz. graphical display of calculated flow patterns, and temperature distribution, and tabulated data for total and average quantities are provided in Appendices, separately for each case. Conclusions of the present study and recommendations for further analysis are presented in Section 4.

Section 2
NUMERICAL MODEL

A numerical model has been developed to calculate velocity and temperature distributions of liquid oxygen (LOX) in a spherical dewar tank. To focus attention to the "Replenish" period, the initial condition is assumed to be quiescent liquid of uniform temperature, up to an appropriate level in the tank. The development of subsequent LOX motion and temperature nonuniformity are calculated by solving the conservation (transport) equations for mass, momentum, energy and two turbulence parameters (viz: turbulent kinetic energy k, and its dissipation rate ε). These equations are solved by using CHAM's general-purpose Computational Fluid Dynamics (CFD) code: PHONEICS [Reference 1], which employs an iterative finite-difference solution procedure.

Further assumptions and salient features of the model are summarized below.

1. Computations are performed for the liquid phase (LOX) only. No heat or mass transfer to the gaseous phase, above LOX, is accounted for.

2. The dewar boiloff heat loadings are specified as heat fluxes through the dewar wall. These heat fluxes are assumed to be distributed uniformaly at the lower quarter of the dewar surface.

3. Flow is treated as transient, three-dimensional, turbulent and elliptic.

4. Fluid is assumed to be incompressible. Density and other fluid properties are calculated as functions of local temeprature. The following fluid properties, linearly related with temperature, have been used. These data are taken from Reference 2.

   - Fluid Density:

     $$\rho = 99.123 - 0.179T \text{ lbm/ft}^3 \tag{2-1}$$

   - Molecular Viscosity:

     $$\mu = (48.943 - 0.219T) \times 10^{-5} \text{ lbm/ft-sec} \tag{2-2}$$

   - Heat Capacity:

     $$C_p = 0.357 + 0.0003T \text{ Btu/lbm}^{o}\text{R} \tag{2-3}$$

- Laminar Prandtl Number:
  $\sigma = 5.998 - 0.0233T$ (2-4)

With the above equations, at $162.9^{o}R$ and 9 psig, LOX has the following values:

ρ = 71.12 lbm/ft^3;
μ = 1.3268×10^{-4} lbm/ft-sec;
C_p = 0.4058 $Btu/lbm^{o}R$;
σ = 2.202.

5. A cylindrical ploar coordinates (x, y, z) system is employed, where x is the circumferential direction, y is the radial direction and z is the longitudinal direction. The parts of calculation domain lying outside the spherical tank and above the liquid level are blocked off by prescribing appropriate "porosity" values. Porosity values are zero for fully blocked cells, unity for unblocked cells, and between 0 and 1 for partially blocked cells.

   Separate values are assigned for the volume and cell-face areas of each control cell. The porosity values determine the proportion of the cell volume which is available for occupancy by the fluid, and the proportion of each cell-face area available for flow. This practice is much more rigorous and accurate than the practice of using rectangular steps.

   The practice of simulating the arbitrary-shaped boundaries by porosities in an orthogonal coordinate system has been successfully used in many applications of both internal and external flows, including for space-shuttle problems [References 3, 4 and 5].

6. To simulate the changes of liquid level with time, porosity values of relevant control cells are updated with time.

7. The wall shear stress is calculated by using the conventional wall functions which are based on the assumption of logarithmic law of wall. For partially blocked control cells, wall shear stress are calculated for the projected surfaces parallel to velocity components.

- Definition

$$u^+ = \frac{u}{\sqrt{\frac{\tau_s}{\rho}}} \qquad (2\text{-}5)$$

$$y^+ = \frac{\rho u \delta}{\mu u^+} \qquad (2\text{-}6)$$

- Logarithmic law of wall

$$u^+ \begin{cases} = \frac{1}{\kappa} \ln E\, y^+; \text{ for } y^+ > 11.5 \\ = y^+; \text{ for } y^+ \leq 11.5 \end{cases} \qquad (2\text{-}7)$$

where τ_s represents shear stress, μ and ρ are molecular viscosity and density of fluid, u is the velocity component parallel to wall in the adjacent control cell, and δ is the distance between the wall and the center of the control cell. Y^+ and u^+ are the normalized distance and velocity as used in the logarithmic law of wall. κ is Von Karman constant, taken equal to 0.4, and E is another empirical constant, which for a smooth surface has the value of 9.0 [Reference 6].

As a consequence, the wall shear stress is simulated by the following:

$$\tau_{wall} = \Gamma_{wall} \frac{\partial u}{\partial y} = \Gamma_{wall} \frac{0-u}{\delta} \qquad (2\text{-}8)$$

where $\Gamma_{wall} \equiv \frac{\mu y^+}{u^+}$ is the friction coefficient for momentum transfer to wall.

8. British units are used in the calculations. However calculated global quantities are printed in both British and S.I. units.

Section 3
TEST CASES AND RESULTS

This section describes the specifications of Test Cases 1 to 4. The input boundary conditions comprise of LOX facility heat loads, replenish flow rates, recirculation flow rates in dewar and dewar boiloff heating. These quantities are prescribed as functions of time. For ready reference, relevant supplied input data are included in Appendix A.

TEST CASE 1

Figure 3-1 shows the selected grid distribution for Test Case 1. A total of 1620 (NX=10, NY=9 and NZ=18) control cells have been used to cover the region of interest, i.e. LOX filled region during replenish time period. Six time steps of 2000 seconds each are used to cover the first 12000 seconds of the replenish period.

The grid distribution near the LOX free surface is so chosen that one row of control cells is emptied in each time step. The porosities of relevant cells are prescribed according to the level changes with time. The model has been checked out for consistency between LOX levels, volumes and flow rates.

As mentioned earlier, the analysis starts at the beginning of replenish time. Liquid oxygen is assumed to be quiscent with $T_o = 162.9^oR$; and p_o = 9 psig. Based on the VAFB LO_2 consumption data (Table A-2), LOX occupies 112975 gallons (15102.56 ft^3) of the dewar with the level of 17.71 ft. measured from the bottom of dewar, at the beginning of replenish.

The following conditions are used as boundary conditions:

- Volumetric inflow from 8"ϕ return pipe is fixed, and is equal to 390 gpm.
- Heat flux (gain) through tank wall is deduced from the LOX dewar heat load boiloff; i.e.
  $\dot{Q}_{flux}$ = 80 lbm/hr x 89.45 Btu/lbm = 7156 Btu/hr

LOX Level Drops in 3.33 hrs (Case 1)

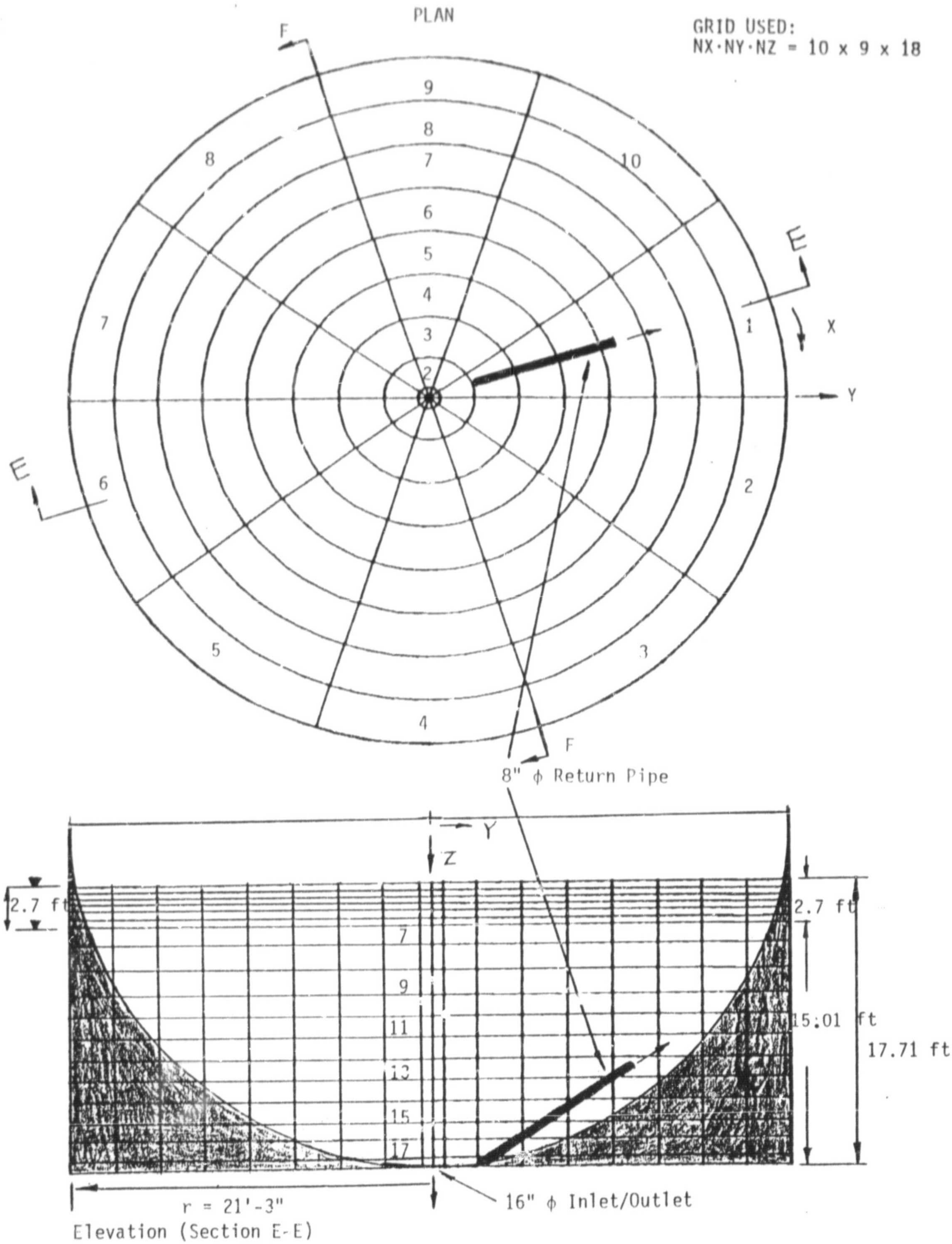


Figure 3-1. Grid Distributions for Case 1

This heat flux is uniformly distributed at the lower quarter of the dewar surface (i.e. for IZ $\geq$ 12, in Figure 3-1).

- The outlet pressure of the liquid oxygen is fixed to a reference value (9 psig). Since the flow is incompressible, this does not influence density or the flow distribution. The liquid level time variations are deduced from the balance of replenish outflow (525 gpm) and recirculation inflow (390 gpm). Specifications of LOX level time variations for this case are given in Table 3-1.

Table 3-1
Specifications of LOX Levels (Case 1)

Time Instant	Time from the start of replenish (sec)	LOX Liquid Volume (ft^3)	Liquid Level (measured from the bottom) (ft)
T_0	0	15102.56	17.71
T_1	2000	14500.96	17.27
T_2	4000	13899.36	16.83
T_3	6000	13297.76	16.38
T_4	8000	12696.16	15.93
T_5	10000	12094.56	15.48
T_6	12000	11492.96	15.01

NOTE: Total LOX Volume Reduction (for whole dewar) in 3.3 hrs = 3609.6 ft^3

- Facility heat load, i.e. heat gained by LOX from dewar outlet to 8"ϕ return inlet, is estimated from the drain line temperature measurement (Figure A-2). The corresponding heat flow through 8"ϕ pipe is:

$$\dot{m}_{in} h_{in} = \rho_{in} \dot{V}_{in} C_p T_{in} \tag{3-1}$$

Based on the overall energy balance and the dewar outlet temperature, the above heat flow is equavalent to a facility heat load, $\dot{Q}$, having the following relationship:

$$h_{in} = C_p T_{out} + \frac{\dot{Q}}{\dot{m}_{in}} \text{ Btu/lbm} \tag{3-2}$$

where T_{out} is the dewar outlet temperature.

Figure 3-4 illustrates the resultant $\dot{Q} \sim$ time variations for this case.

TEST CASE 2

For Case 2, the geometry and flow conditions are the same as for Case 1. However there are the following differences in numerical parameters.

1. Only half of the dewar is simulated due to the symmetry of both geometry and boundary conditions imposed.
2. Finer grid distribution is used in the circumferential direction.
3. Calculation duration is extended up to 5½ hours, instead of 3½ hours. Hence the calculations cover the whole replenish and also the additional hold periods. Nine time steps are used; with ΔT = 2000S for the first seven time intervals and ΔT = 2800S and 3000S for eighth and ninth time steps, respectively.

Figure 3-2 shows the grid distributions. A total of 1944 (NX=12, NY=9 and NY=18) control cells have been used. Specifications of LOX level $\sim$ time variations for Case 2 are given in Table 3-2.

Table 3-2

Specifications of LOX Levels (Case 2)

Time Instant	Time From the start of Replenish (sec)	LOX Liquid Volume (ft^3)	Liquid Level (measured from the bottom) (ft)
T0	0	15102.56	17.71
T1	2000	14500.96	17.27
T2	4000	13899.36	16.83
T3	6000	13297.76	16.38
T4	8000	12696.16	15.93
T5	10000	12094.56	15.48
T6	12000	11492.96	15.01
T7	14000	10890.[illegible]	14.55
T8	16800	10050.00	13.88
T9	19800	9146.50	13.14

LOX Volume Reduction for Whole Dewar in 5.5 hrs = 5956.06 ft^3

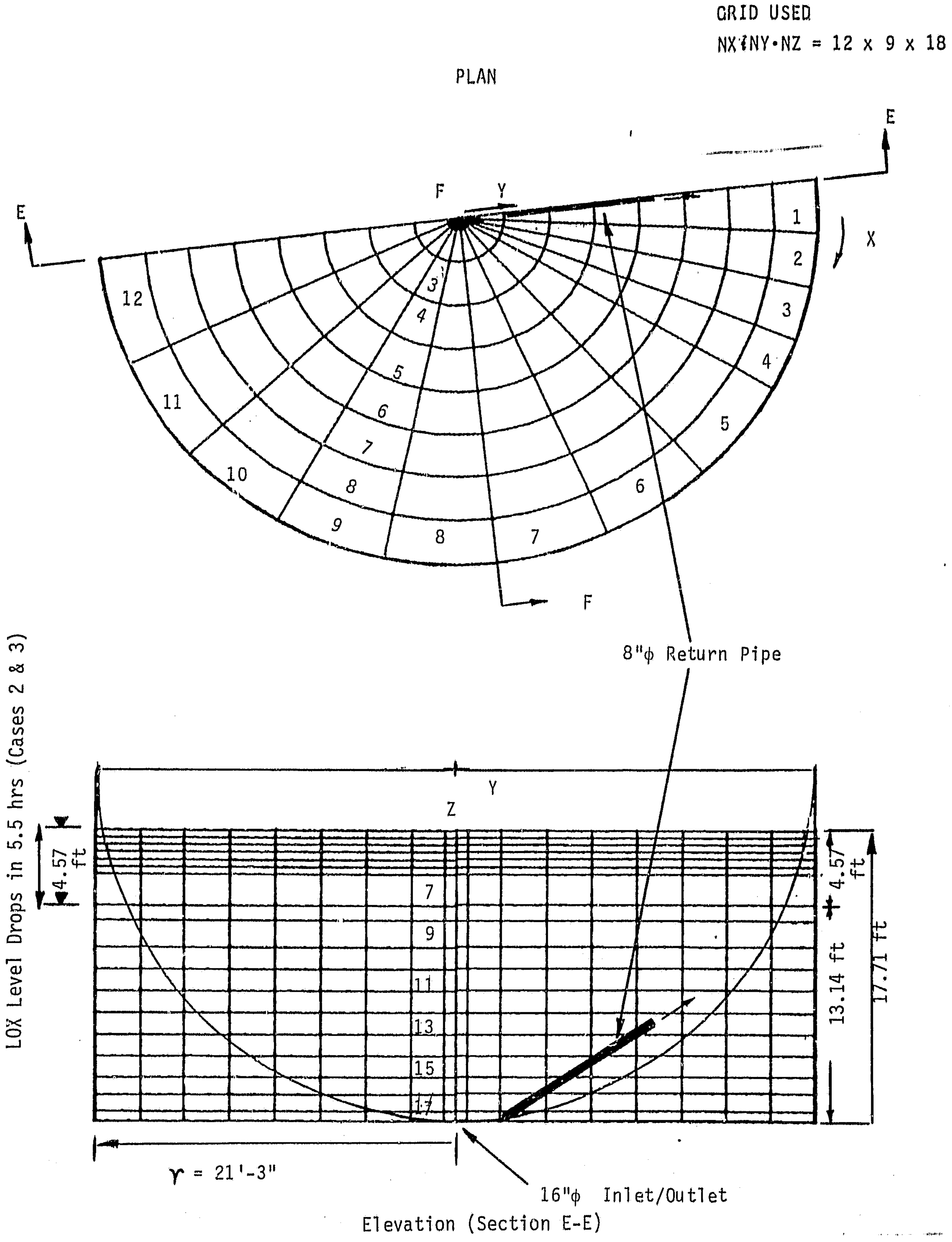


Figure 3-2. Grid Distributions for Cases 2 and 3

TEST CASE 3

Specifications of Cases 3 and 4 were determined after the study of results for Cases 1 and 2. Case 3 is identical to Case 2, except for the prescription of a constant heat load ($\dot{Q} \equiv 231,226$ Btu/hr) throughout the replenish period (Figure 3-4). Grid distribution and specification of LOX level $\sim$ time variations for Case 3 are given in Figure 3-2 and Table 3-3, respectively.

Table 3-3
Specifications of LOX Levels (Case 3)

Time Instant	Time From the Start of Replenish (sec)	LOX Liquid Volume (ft^3)	Liquid Level (Measured From The Bottom) (ft)
T_0	0	15102.56	17.71
T_1	2000	14500.96	17.27
T_2	4000	13899.36	16.83
T_3	6000	13297.76	16.38
T_4	8000	12696.16	15.93
T_5	10000	12094.56	15.48
T_6	12000	11492.96	15.01
T_7	14000	10890.00	14.55
T_8	16000	10290.00	14.07
T_9	18000	9688.00	13.59
T_{10}	19800	9146.50	13.14
LOX Volume Reduction in Whole Dewar in 5.5 hrs = 5956.06 ft^3			

TEST CASE 4

For Case 4, all but one condition are specified to be identical to those of Case 3. The changed condition is the lower LOX level at the start of replenish period such that at the end of 5½ hours replenish period, LOX level is close to the top of 8"ϕ return pipe. Grid distribution and specification of LOX level $\sim$ time variations for Case 4 are given in Figure 3-3 and Table 3-4, respectively.

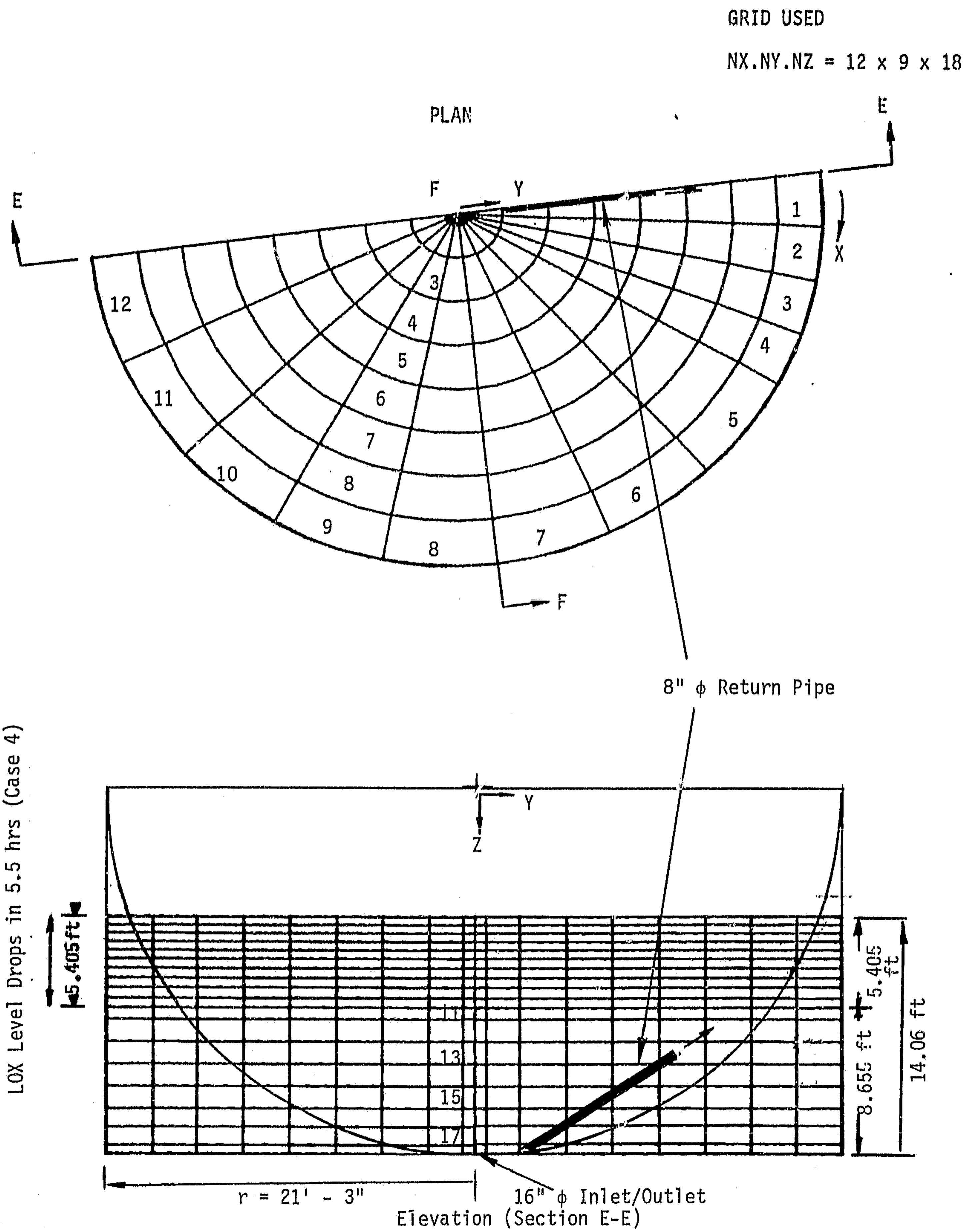


Figure 3-3. Grid Distributions for Case 4

Table 3-4

Specifications of LOX Levels (Case 4)

Time Instant	Time From the Start of Replenish (sec)	LOX Liquid Volume (ft^3)	Liquid Level (Measured From The Bottom) (ft)
T_0	0	10272	14.06
T_1	2000	9670.4	13.57
T_2	4000	9068.8	13.08
T_3	6000	8467.2	12.58
T_4	8000	7865.6	12.06
T_5	10000	7264	11.53
T_6	12000	6662.4	10.99
T_7	14000	6060.8	10.42
T_8	16000	5459.2	9.839
T_9	18000	4857.6	9.229
T_{10}	19800	4315.94	8.655

NOTE: Total Volume in Whole Dewar in 5.5 hrs = 5956.06 ft^3

Heat Flux Through 8"ϕ Return Pipe

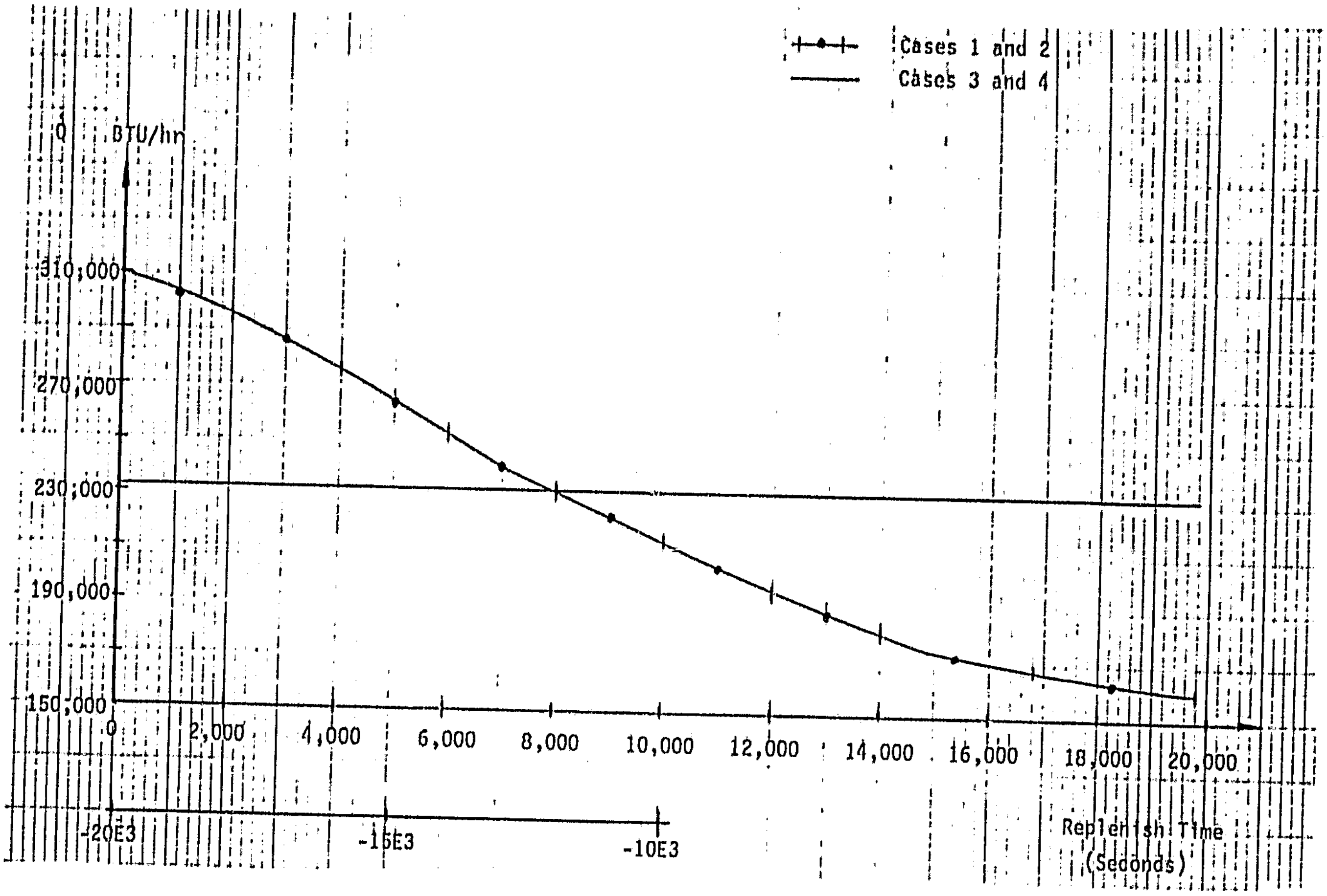


Figure 3-4. Facility Heat Load Variations

PRESENTATION OF RESULTS

For each case, results are presented in the following forms.

1. Velocity vectors and liquid temperature contours at selected horizontal and vertical planes (Appendices B, C, D and E).
2. Global parameters printout (Appendicies F to H) for the time variations of the following quantities:
   - average temperature and density;
   - resident mass of liquid oxygen in the tank;
   - resident thermal energy in dewar.
3. Liquid temperature ∿ time variation diagrams, (Figures 3-5 - 3-8); these include temperatures near the entry (8"ϕ inlet), exit (16"ϕ outlet), and the LOX average temperature.

DISCUSSION OF RESULTS

Velocity Distribution (Case 1)

The flow development within the LOX storage dewar is shown by velocity vector diagrams in Appendix B. Figure B-1 presents vector diagrams for the horizontal plane passing through the injection point of the 8"ϕ return pipe, and for the vertical plane containing both inlet and outlet pipes. Figure B-1 is for t = 4000 seconds. Similar diagrams for t = 12000 s are presented in Figure B-2. The last set of diagrams are for a normal vertical plane marked as section F-F in Figures B-5 and B-7.

The main observations from the velocity vector diagrams (Figures B-1 and B-2) are:

1. The jet spreading and turning for the 8"ϕ return pipe show plausible trends. Three recirculation zones are created, one above the 8"ϕ return pipe, and the other two along the tank wall (due to the buoyancy effect).
2. Strong flow motion is observed:
   a) near the jet spreading region;
   b) at the surface of LOX;
   c) near the dewar tank surface; and
   d) at the outlet.

As a consequence of the nonuniform velocities, nonuniform heat transfer coefficients are expected near the wall.

3. Recirculating eddies have been well developed at the late replenish time (at 12000 secs).

Temperature Contours (Case 1)

Isothermal contours at early and late times are also presented in Figures B-3, B-4, B-6 and B-8. As can be seen in these diagrams, the hot zone is concentrated in the jet region and the cold fluid is located at the bottom of dewar.

Velocity Distribution and Temperature Contours (Cases 2-4)

Figures C-1 to C-12 through E-1 to E-12 present results of Cases 2, 3 and 4 in the same form as used for Case 1.

Effect of Grid Refinement

The comparison between Cases 1 and 2 presented in Figure 3-5 shows that except for the liquid temperature near the 8"ϕ return pipe , the temperatures are not sensitive to grid refinements.

Effect of Replenish Time Duration

Velocity vector diagrams for Case 2 are similar to those of Case 1. However, the thermal boundary layer effect near the tank surface becomes more profound at the late time, i.e. 5½ hours from replenish start. Figures C-3 and C-11 show that all near-wall fluid moves towards the wall and has an upward motion. This indicates that at late replenish times, thermal boundary layer type motion becomes more important than that of inlet jet entrainment.

Effect of Facility Heat Loading

Figures 3-6 and 3-7 show liquid temperature variations with time for Cases 2 and 3, respectively. Decrease in temperature rises in Case 2 (Figure 3-6) is due to the reduced facility heat load used (see Figure 3-4).

Effect of Initial LOX Level

The comparison between Cases 3 and 4 presented in Figures 3-7 and 3-8 show that:

1. An increase in temperature rise in Case 4 (as compared to Case 3, Figures 3-7 and 3-8) is due to the smaller LOX volume in dewar.
2. Velocity vector diagrams (Figures E-1 to E-12) are similar as in Cases 1, 2 and 3. However, the fluid motion in Case 4 is stronger that in Case 3.
3. Temperature contours show similar patterns in all cases. However, comparison between results of Cases 2 and 4 shows, as expected, that the smaller LOX volume gives higher temperature level.

In all cases, exit temperature of LOX tends to approach the average temperature towards the end of replenish period.

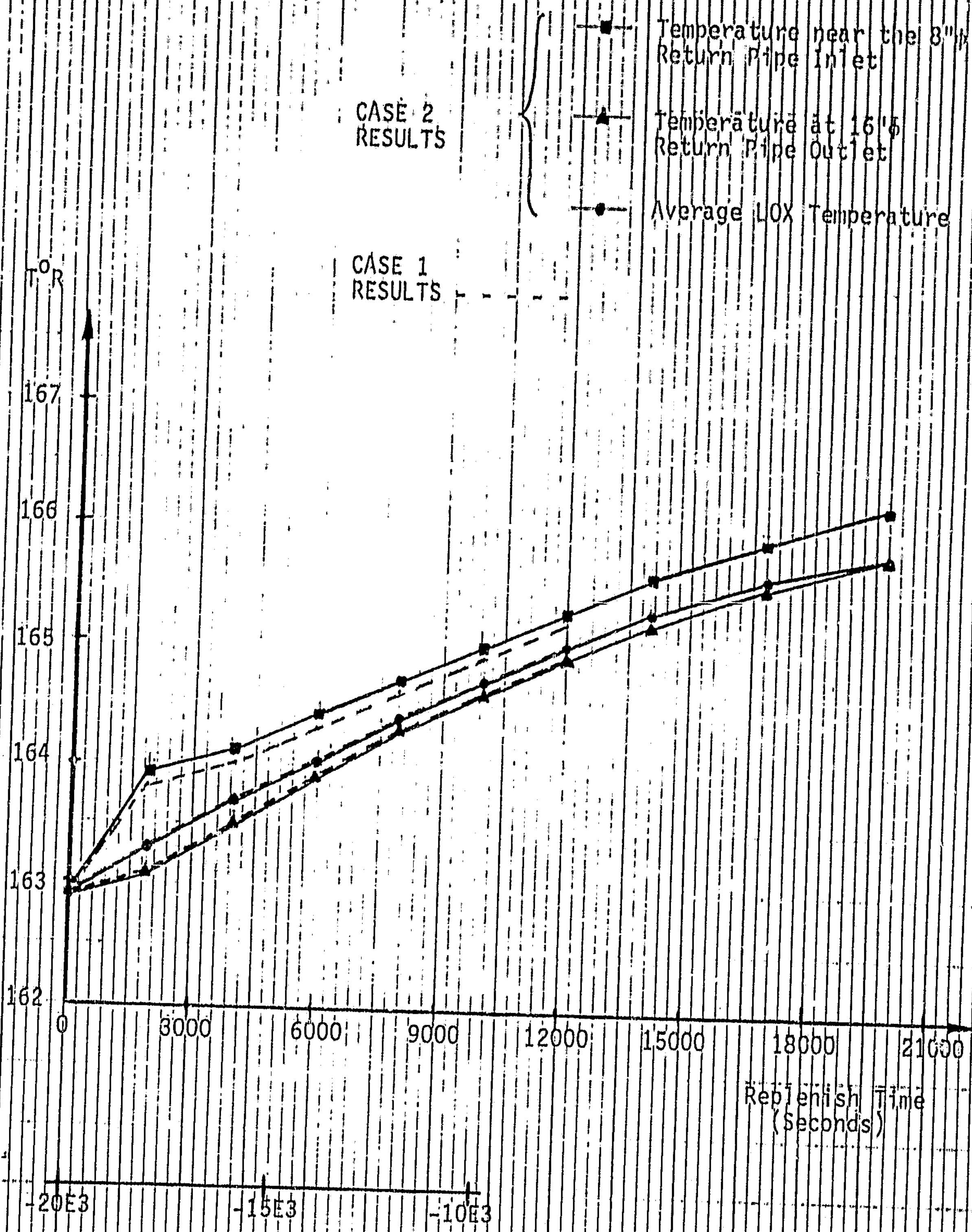


Figure 3-5. LOX Liquid Temperature Variations (Cases 1 and 2)

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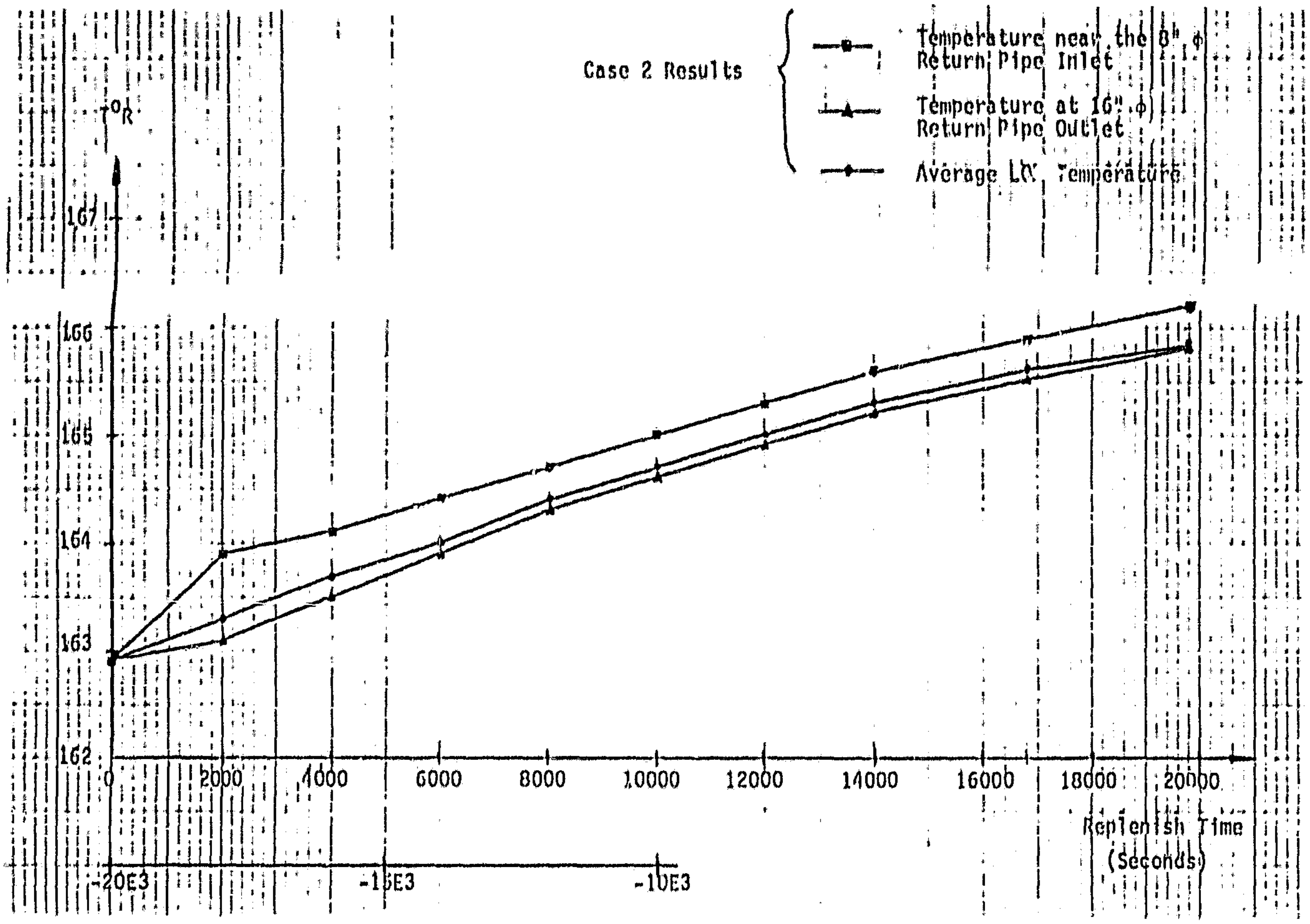

Figure 3-6. LOX Liquid Temperature Variations (Case 2)

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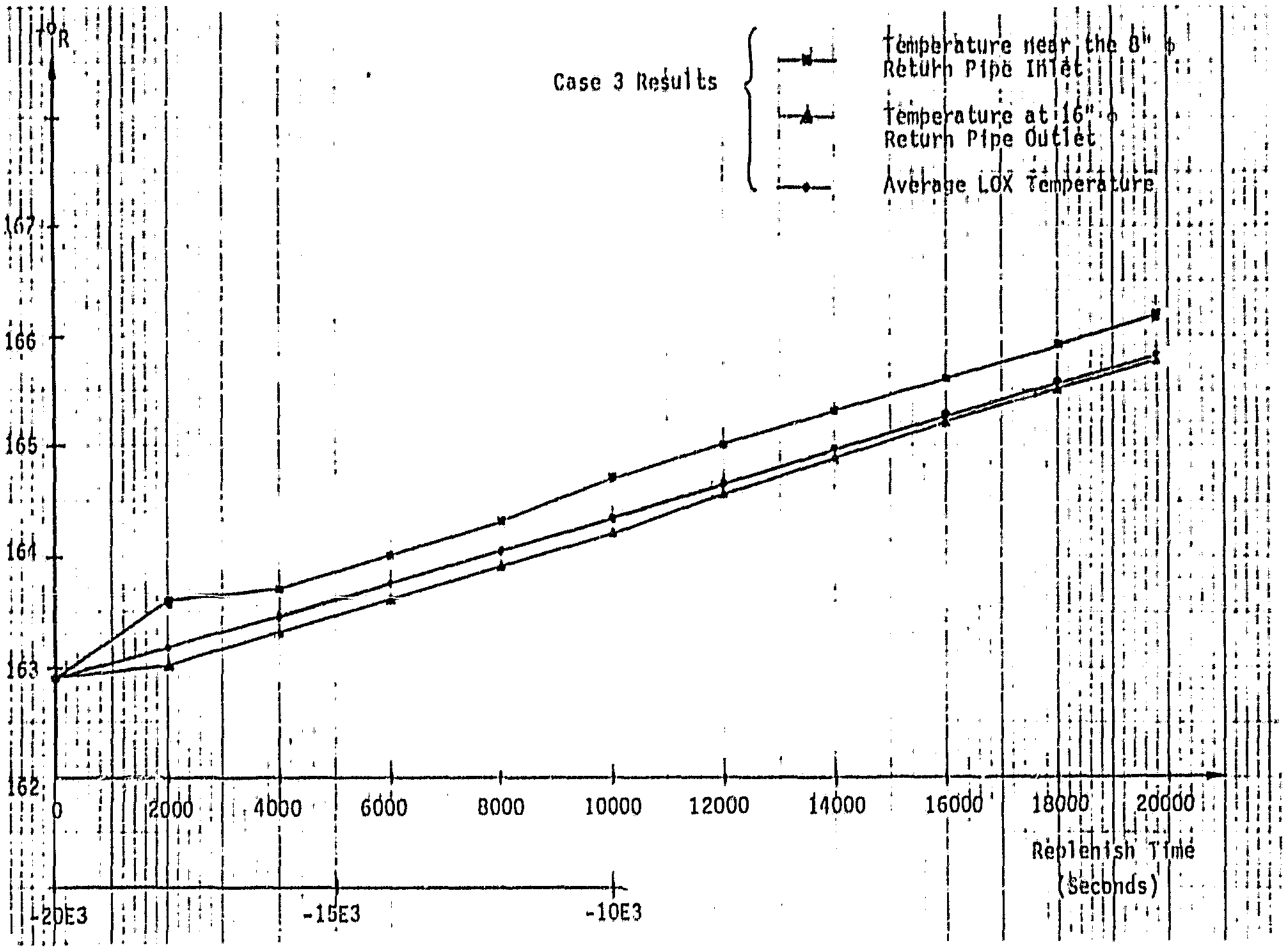

Figure 3-7. LOX Liquid Temperature Variations (Case 3)

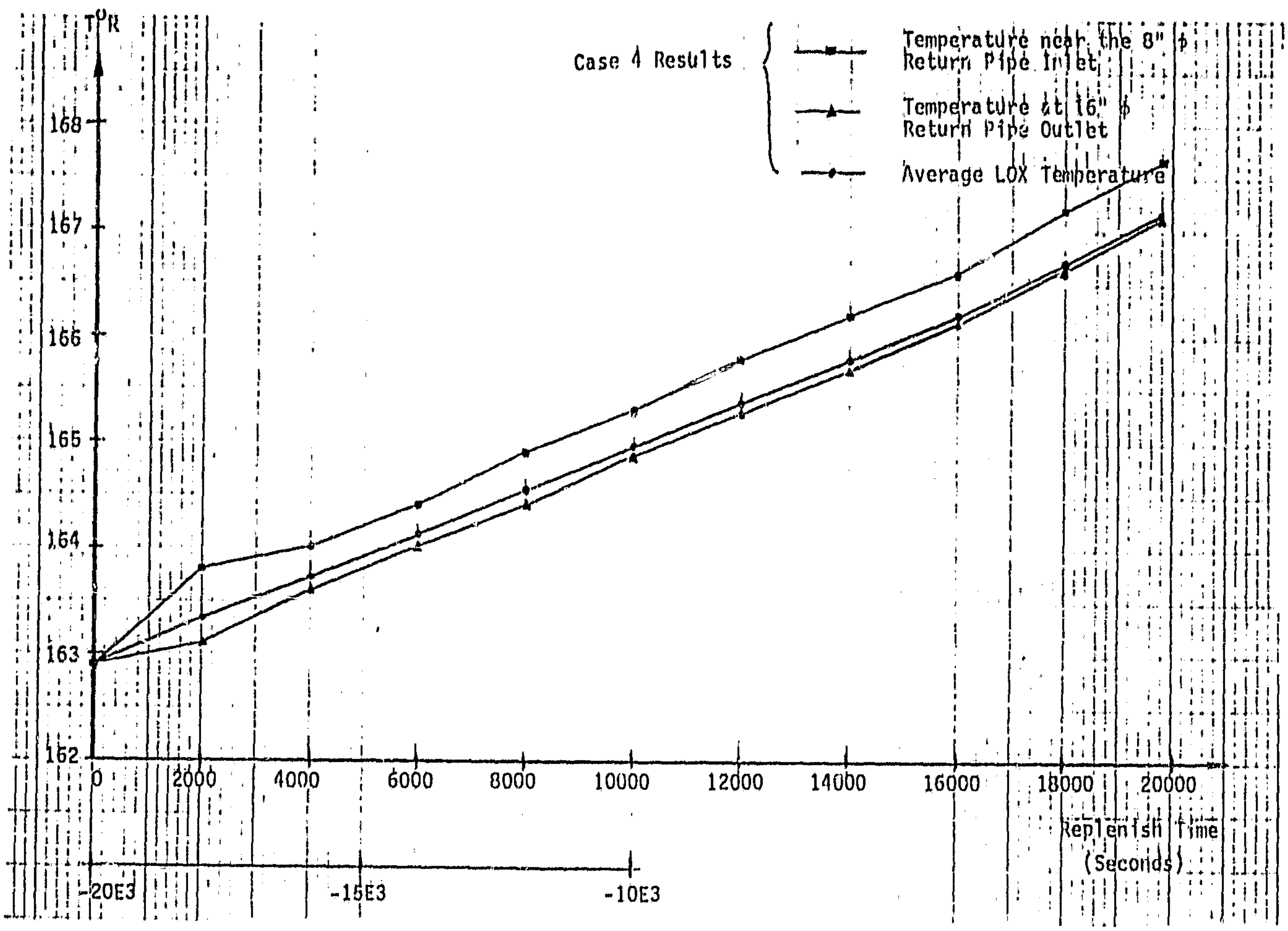

Figure 3-8. LOX Liquid Temperature Variations (Case 4)

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Section 4
CONCLUSIONS AND RECOMMENDATIONS

The main findings of the calculations presented in Section 3, are summarized below.

1. Results of Cases 1 and 2 show that temperatures are not sensitive to grid refinements, except for the liquid temperature near the 8"ϕ return pipe. This provided a basic check on the numerical model.

2. Calculated velocity and temperature distributions for all cases show plausible flow patterns which develop due to: (a) the falling liquid level; (b) the LOX flow through 8"ϕ and 16"ϕ pipes; and (c) the gains of heat through dewar wall, and 8"ϕ return pipe.

3. Computer time requirements were modest. For example, 300 seconds of CPU time on Perkin-Elmer computer were used for each time step with 1944 control cells.

The results and analysis presented in this report have demonstrated the feasibility of simulating LOX flow and heat transfer details in the dewar tank considered. Such simulations can assist in the reduction of temperature exceedances during ET system heat loadings.

Further analyses with different heat flux distributions through wall and different system heat loads are recommended.

Section 5
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APPENDIX A

Supplied Input Data for the Flow and Heat Transfer Analysis of the VAFB LOX Storage Dewar Tank

VAFB O_2 Loading

- O_2 Dewar Heat Load Boiloff 80lb/HR.
- Start loading with 93% O_2 in dewar.
- Assume Replenish flowrate from dewar - 525 gpm.
- Recirculation flow in dewar (during replenish only) 390 gpm.
- Initial O_2 Condition - Saturated at 1 Atmosphere.
- O_2 Dewar presurized to 9 psig at initiation of chill and remains there throughout replenish.
- Facility Heat load from Dewar outlet to return inlet - 310,000 Btu/Hr

VAFB LO2 CONSUMPTION

PROCEDURE TIME	ENGINE BLEEDS GALLONS/GPM	ET VENT GALLONS/GPM	FACILITY COOLDOWN GALLONS	IN ORBITER GALLONS	TOTAL LO2 GALLONS
Chilldown (17 min)	425/25	510/30	2,585	4,260	7,780
Drain Back (10 min)	250/25	300/30	175		725
Slow Fill (12 min)	600/50	360/30	420	2,330	3,710
Fast Fill (30 min)	3,600/120	900/30		142,310	146,810
Topping (20 min)	2,400/120	600/30	700	3,300	7,000
Replenish (3 hr.-25 min)	24,600/120	6,150/30	7,175		37,925
LO2 Storage Tank Boiloff 4 hr-54 min			1,833		1,833
Total LO2	31,750	8,820	12,888	152,220	205,783
2 HOUR ADDITIONAL REPLENISH					22,200
Total LO2					227,983
			RESIDUAL IN TANK		51,017

22ND PSIG AGENDA ITEM VIII.B TIM MEEHAN 14

VAFB LH_2 AND LO_2 LOADING TIMELINE

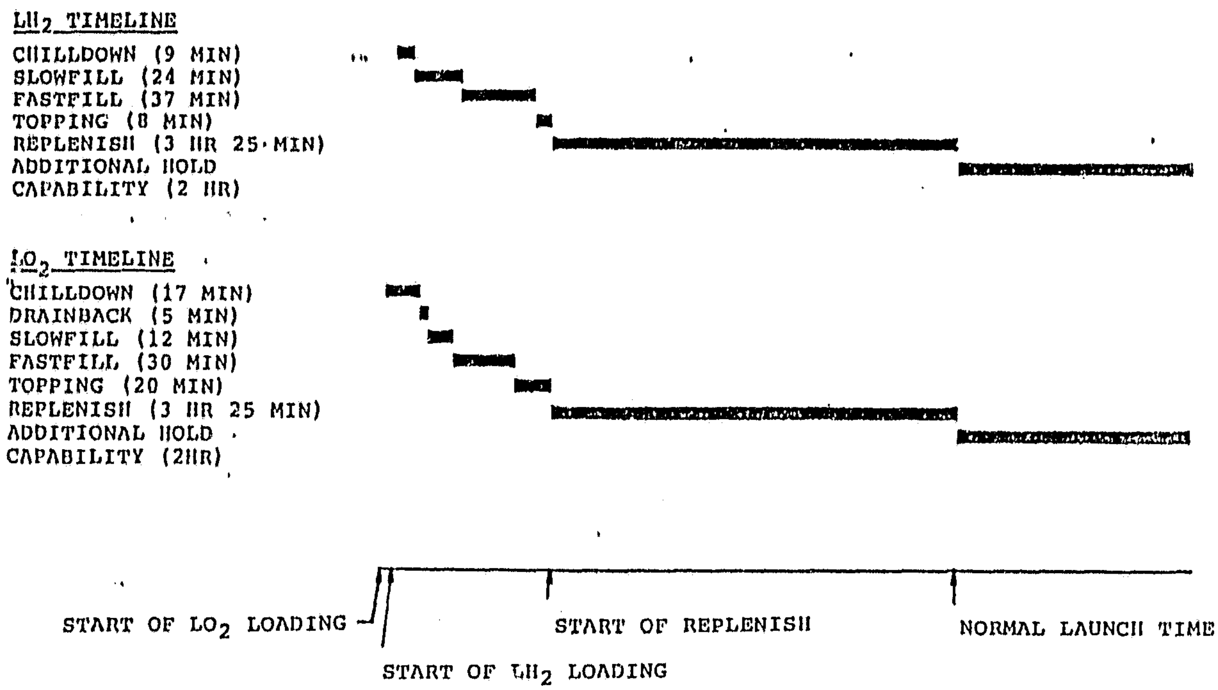


Figure A-1

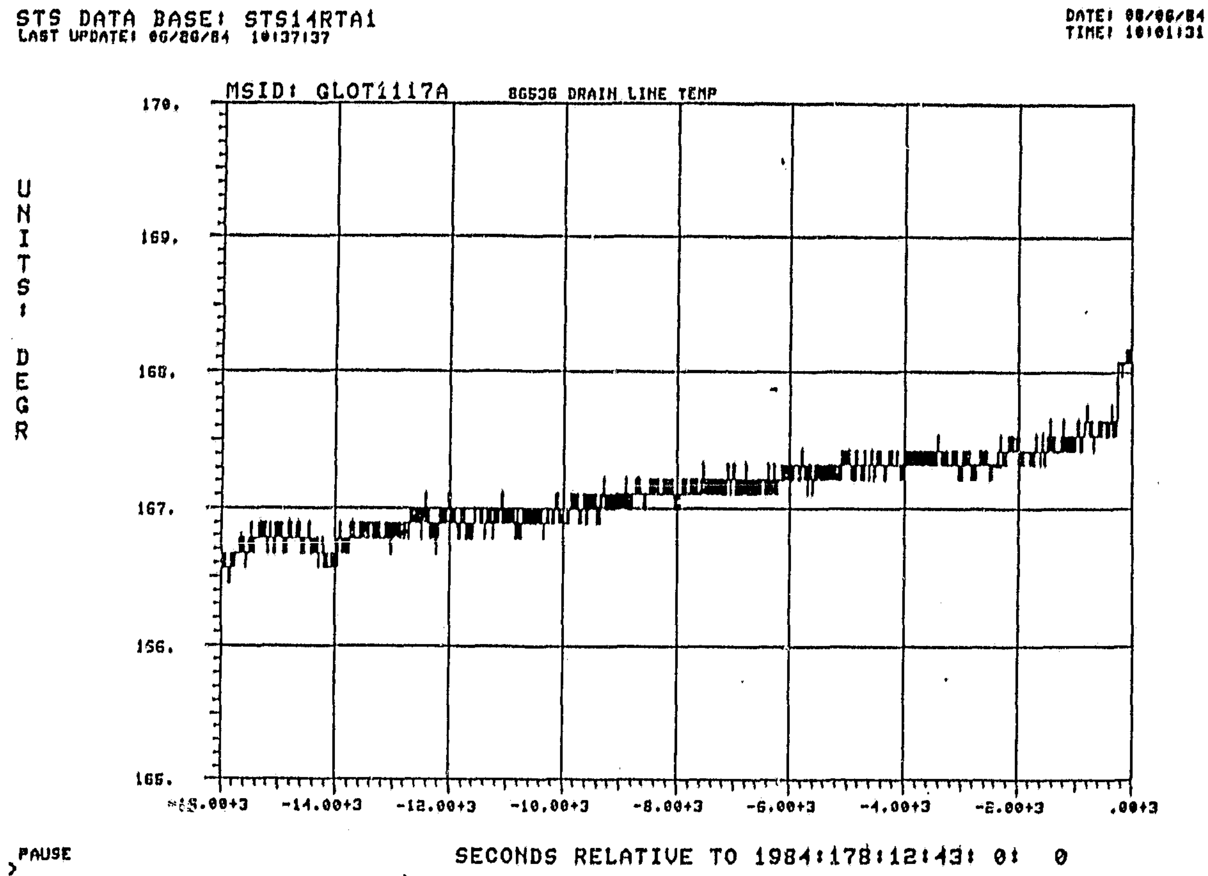


Figure A-2 Drain Line Temperature Measurement.

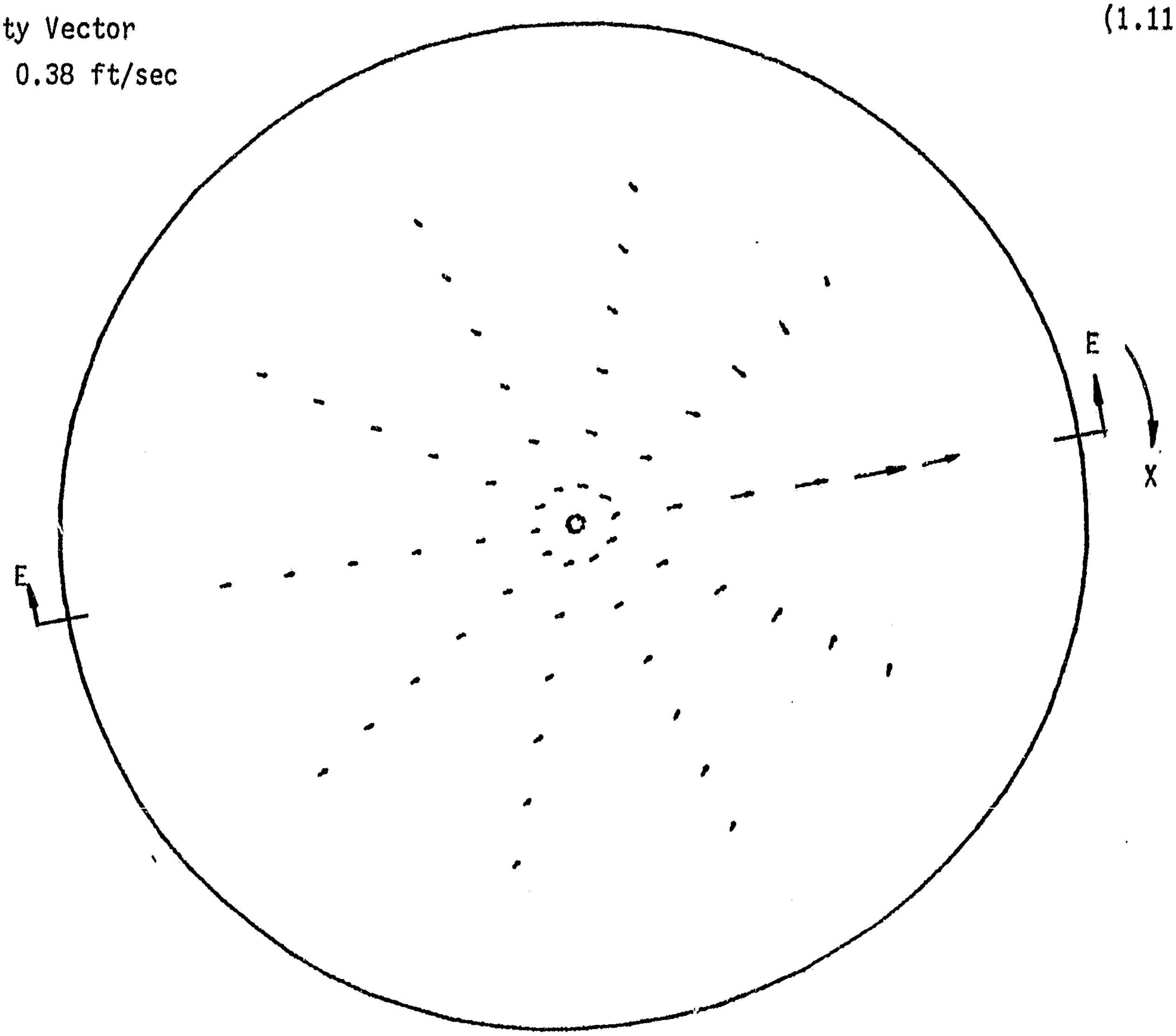
APPENDIX B

Graphical Results (Velocity Vector Diagrams and Temperature Contours) of Test Case 1

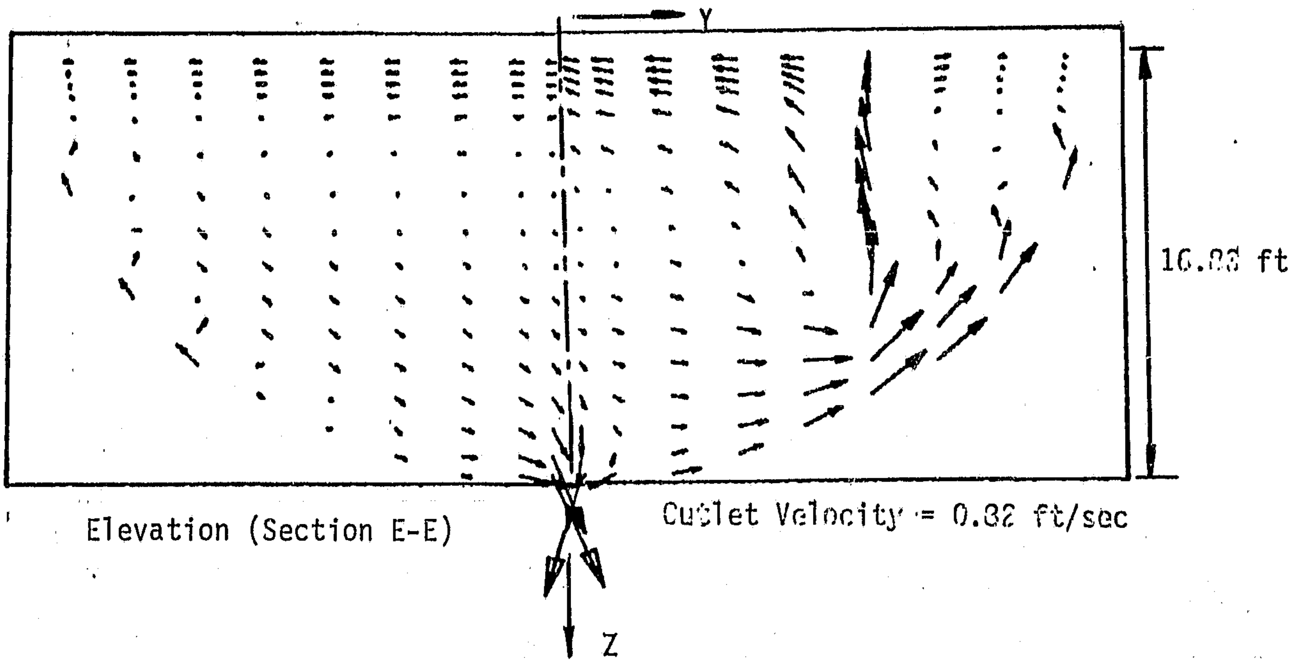
Case 1

t = 4000s
(1.11 hrs)

Velocity Vector
VMAX = 0.38 ft/sec



Plan view just above the return pipe; IZ = 13 in Figure 3-1.



Elevation (Section E-E)

Outlet Velocity = 0.3? ft/sec

Figure B-1 Velocity Vector Diagrams at t = 4000s

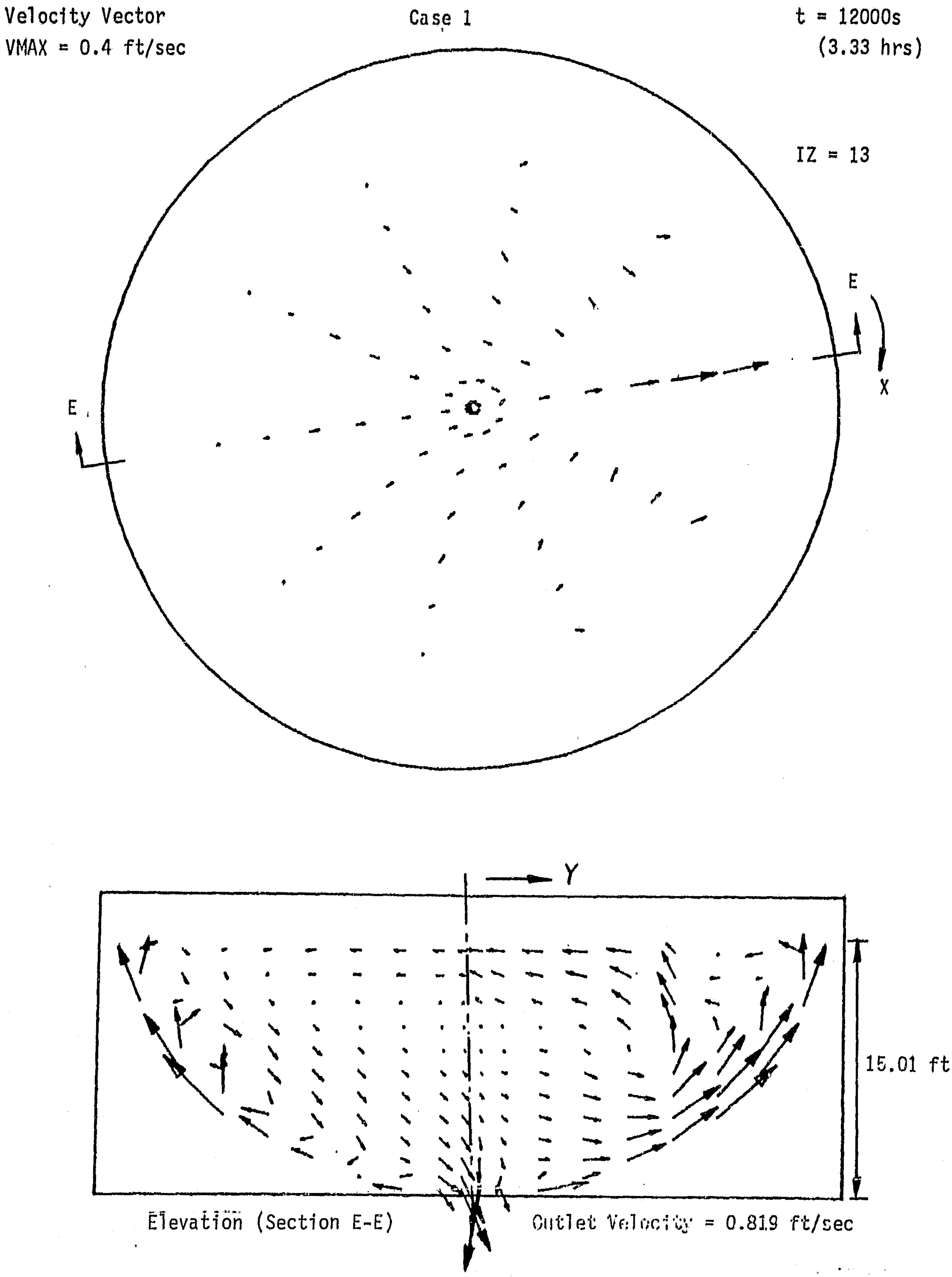


Figure B-2 Velocity Vector Diagrams at t = 12000s

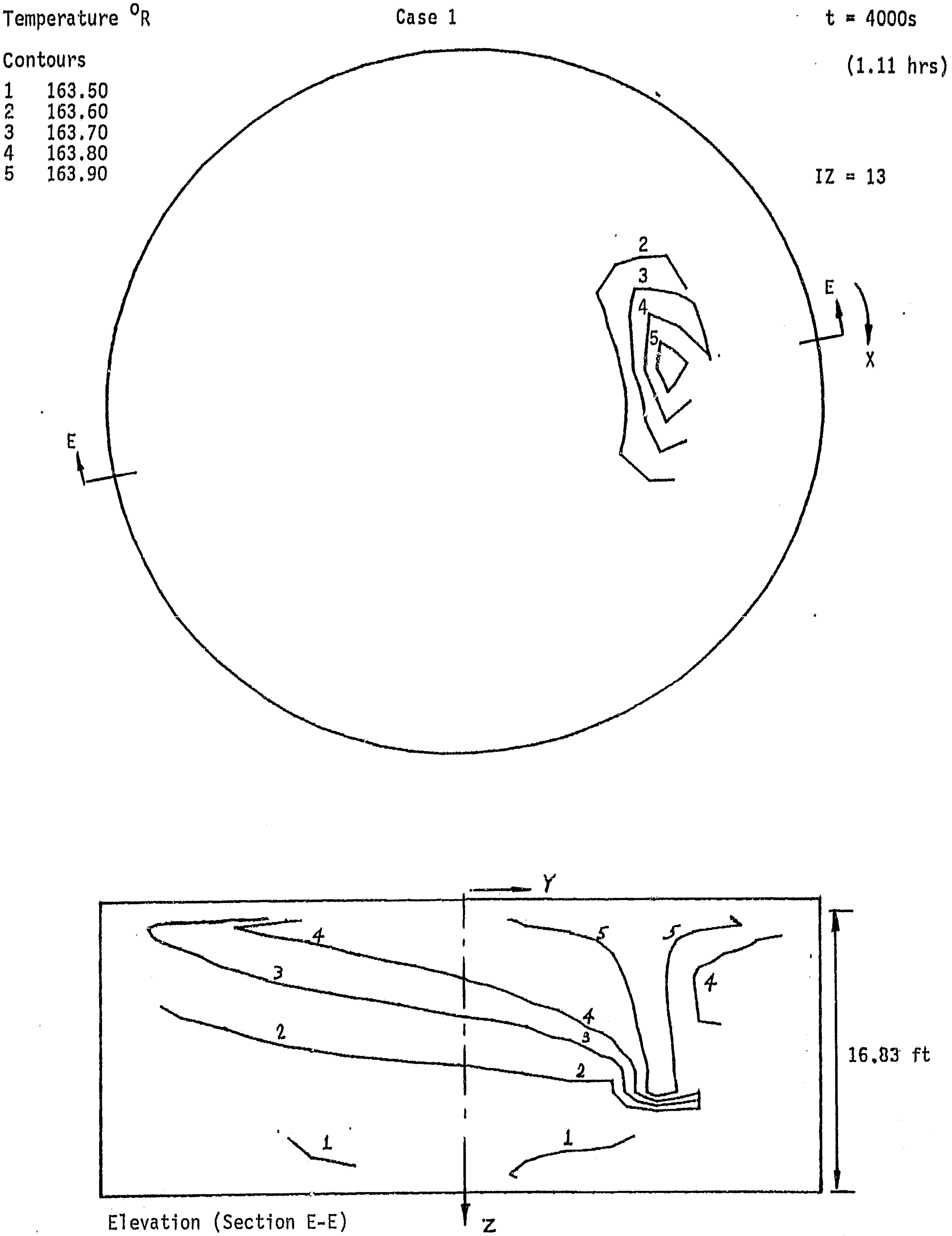


Figure B-3 Temperature Contours at t = 4000s

Temperature ^{o}R

Contours

6	164.90
7	165.00
8	165.05
9	165.10
10	165.15
11	165.20

Case 1

t = 12000s
(3.33 hrs)

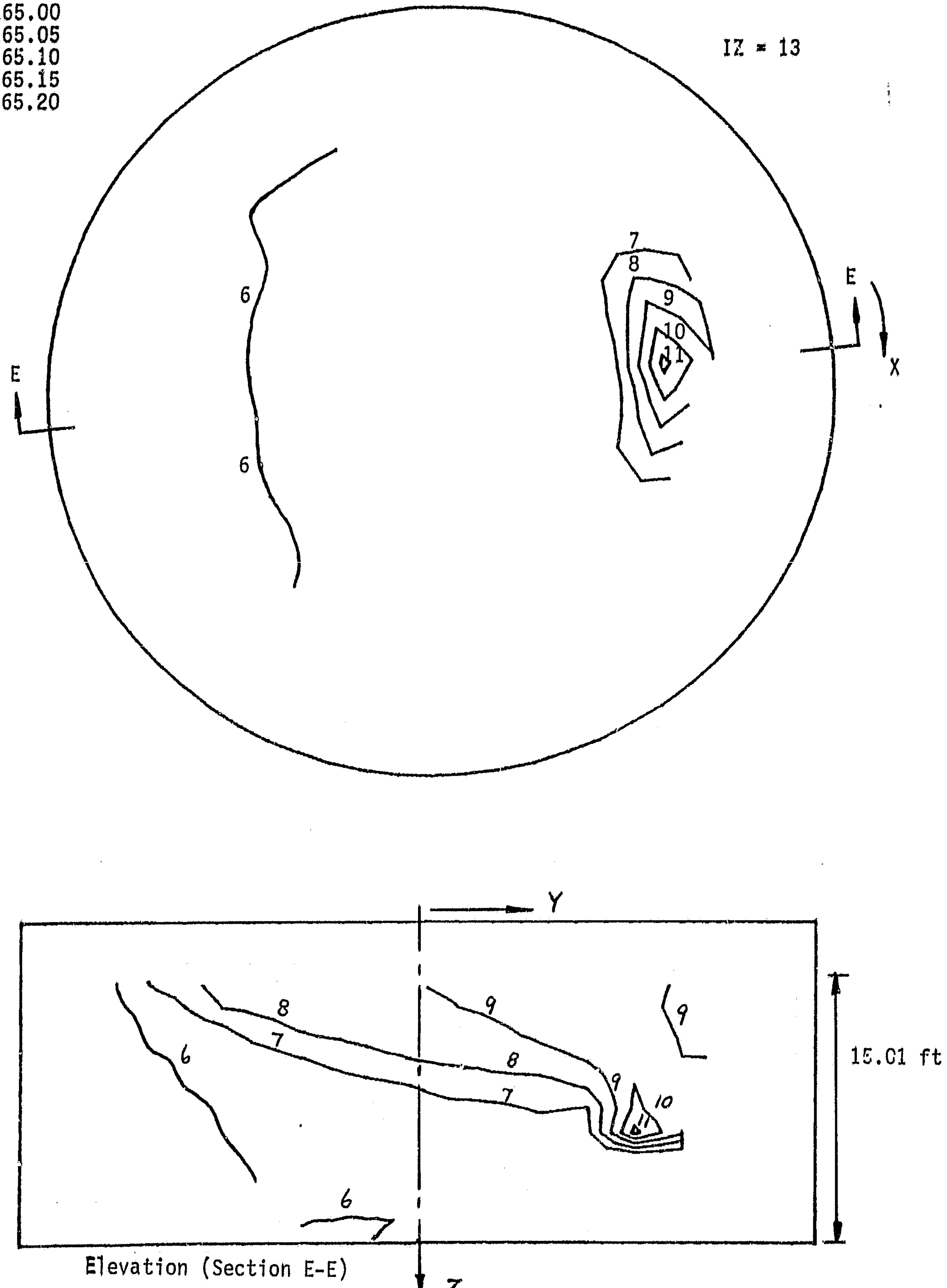


Figure B-4 Temperature Contours at t = 12000s

VMAX = 0.38 ft/sec

Case 1 t = 4000s (1.11 hrs)

Elevation (Section F - F)

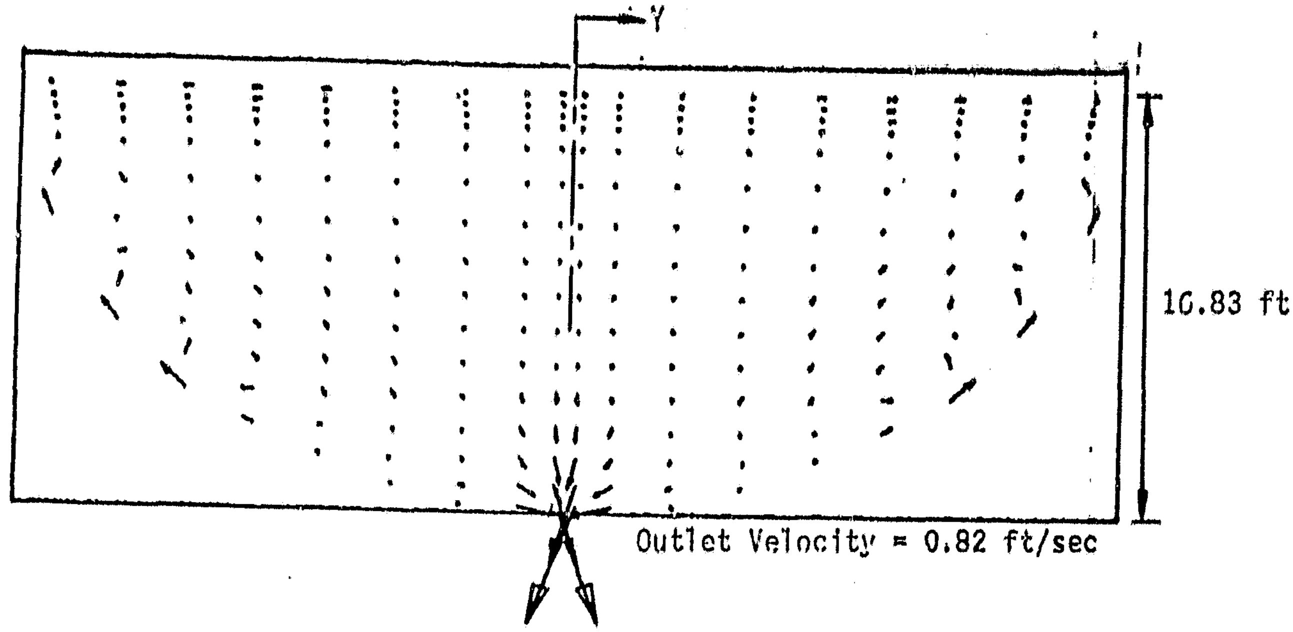


Figure B-5 Velocity Vectors at t = 4000s

Temperature ^{O}R

Contours

1 163.50
2 163.60
3 163.70
4 163.80

Case 1 t = 4000s (1.11 hrs)

Elevation (Section F - F)

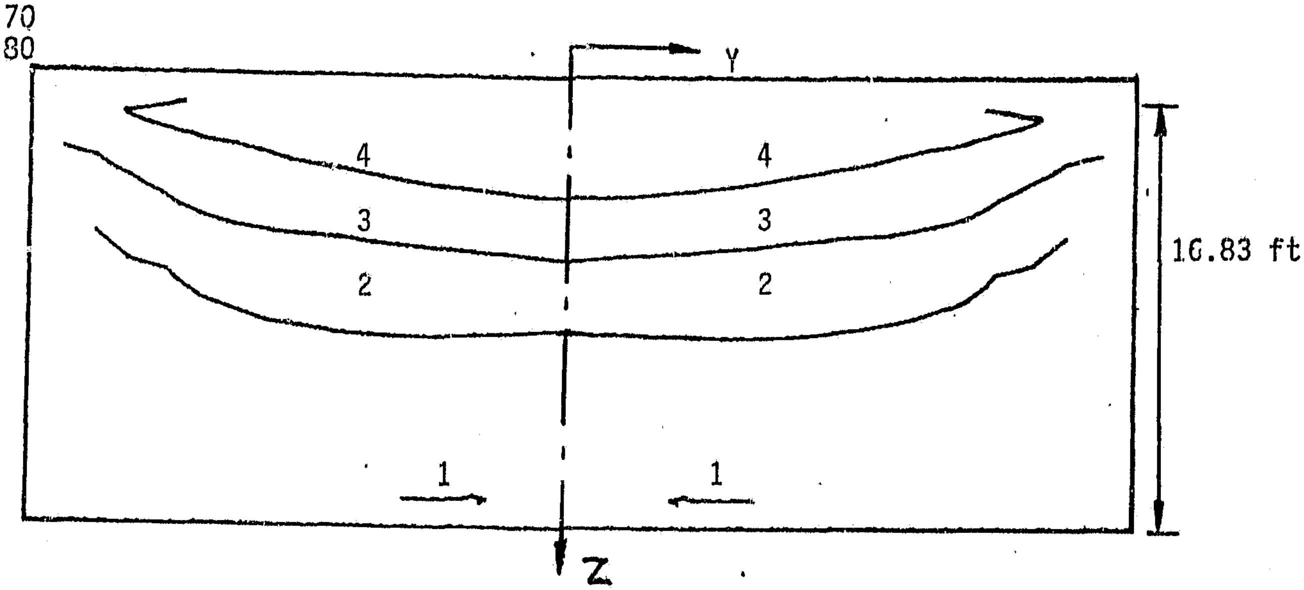


Figure B-6 Temperature Contorus at t = 4000s

VMAX = 0.4 ft/sec   Elevation (Section F - F)   Case 1   t = 12000s

(3.33 hrs)

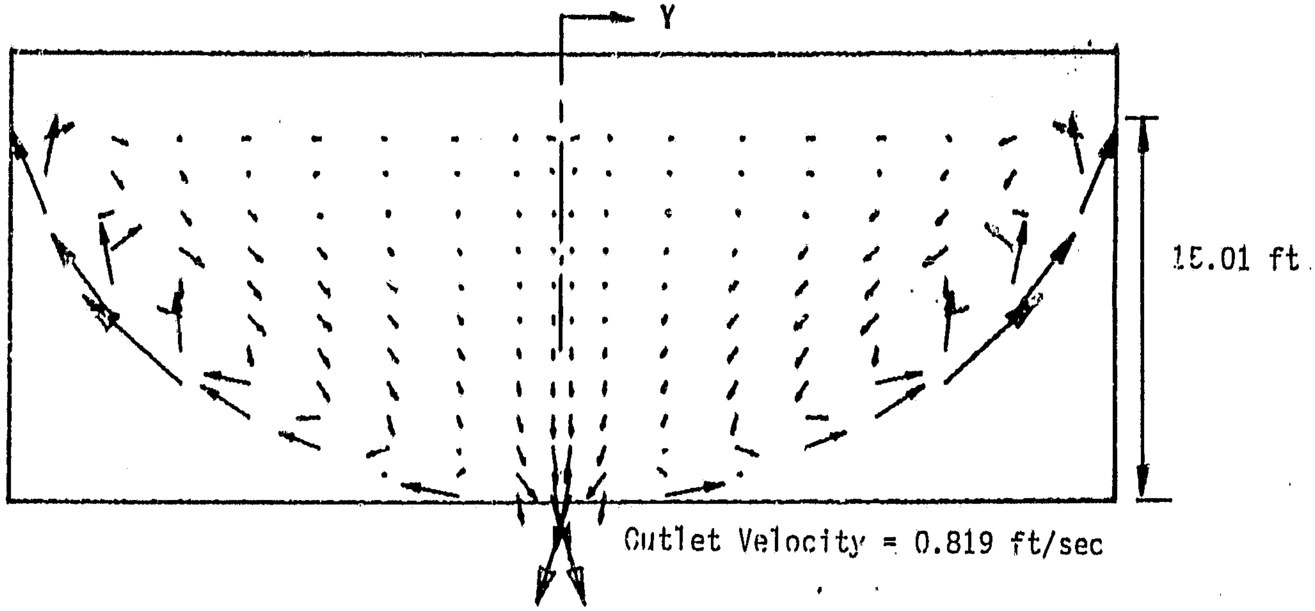


Figure B-7 Velocity Vectors at t = 12000s

Temperature ^oR Case 1   t = 12000s

Contours   Elevation (Section F - F)   (3.33 hrs)

6   164.90
7   165.00
8   165.05
9   165.10

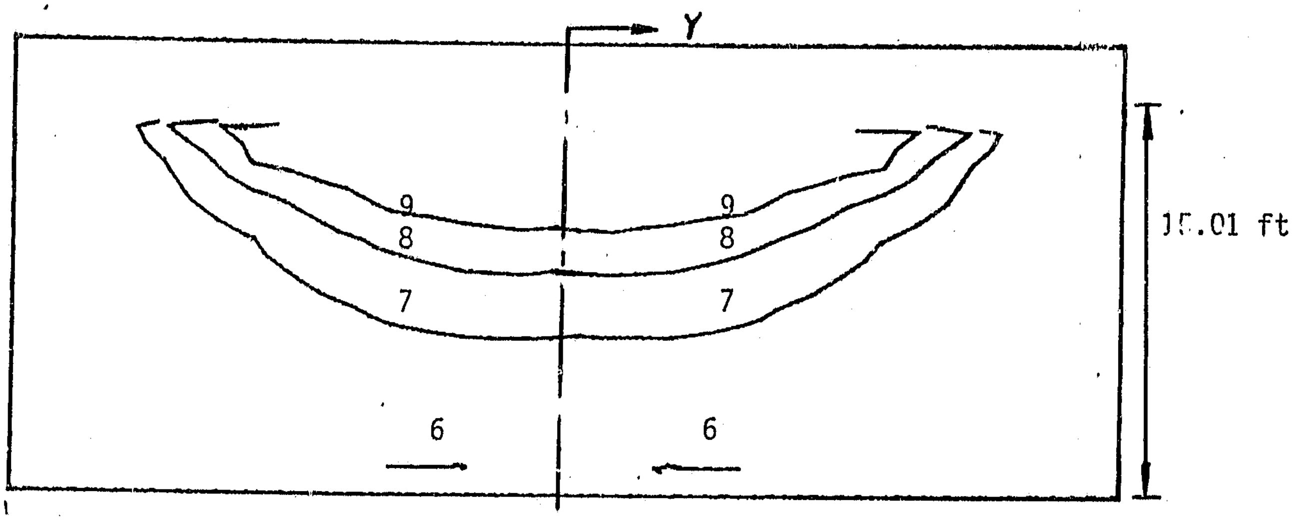


Figure B-8 Temperature Contours at t = 12000s

APPENDIX C

Graphical Results (Velocity Vector Diagrams and Temperature Contours) of Test Case 2.

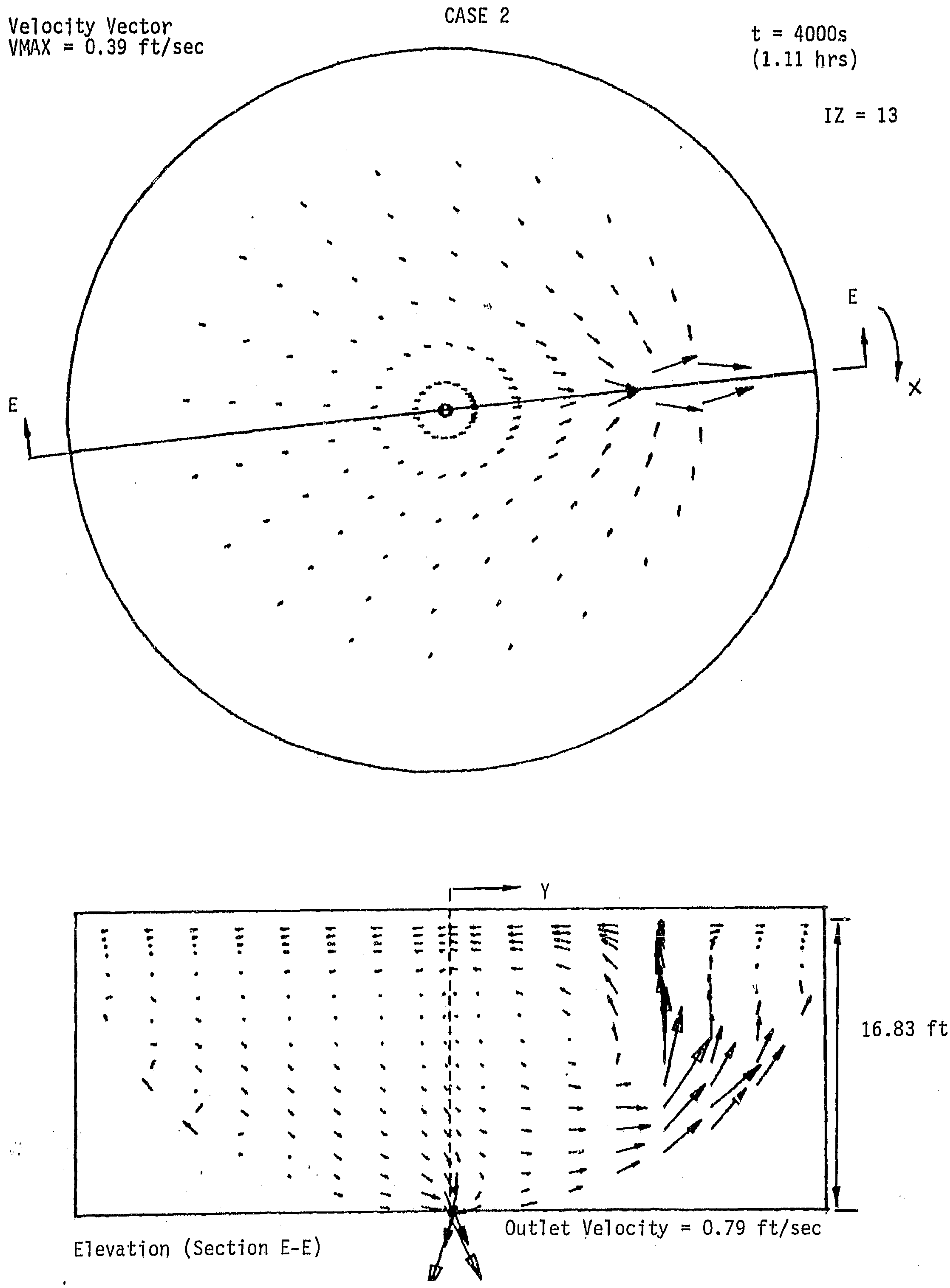


Figure C-1 Velocity Vector Diagrams at t = 4000s

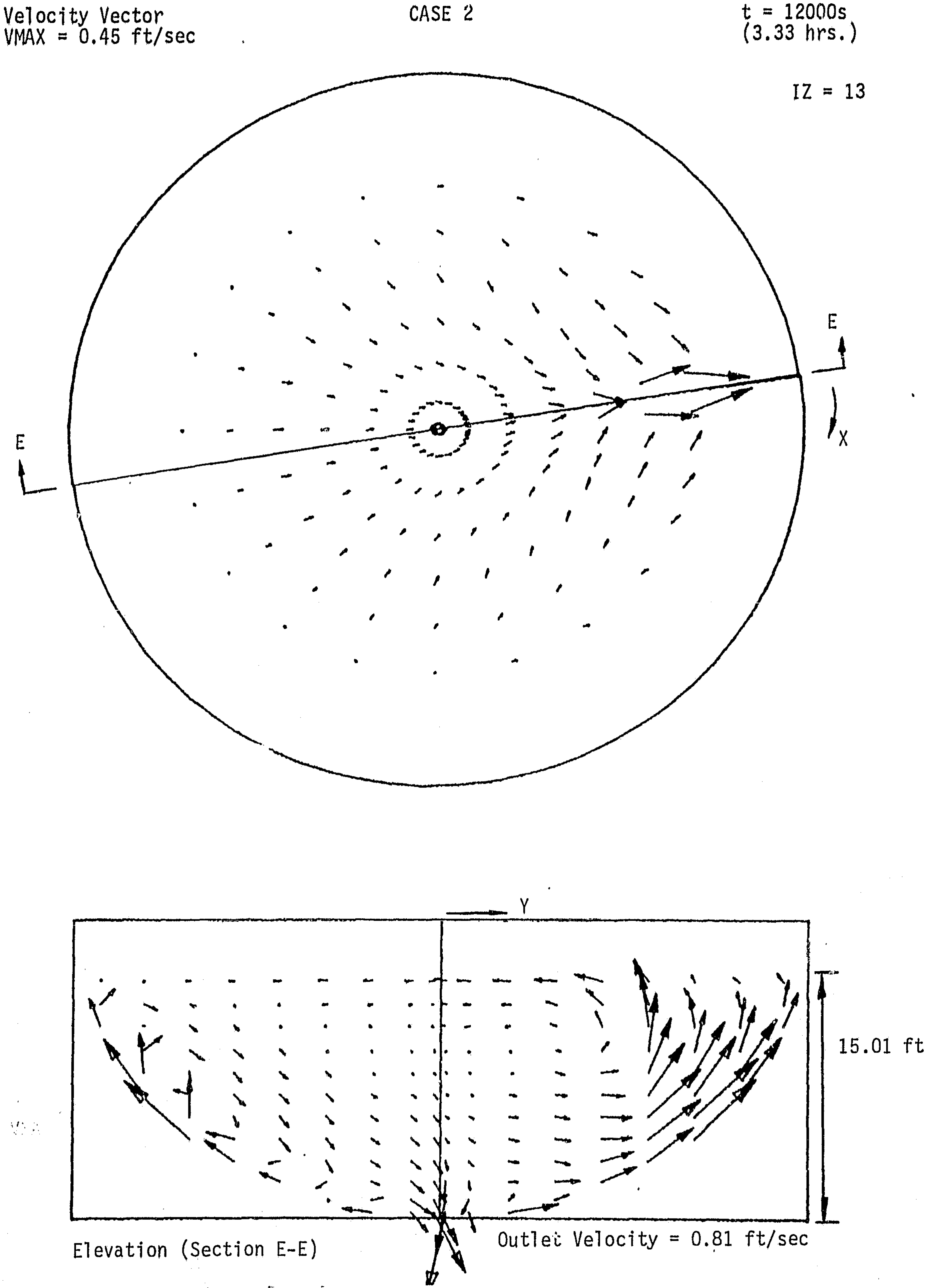
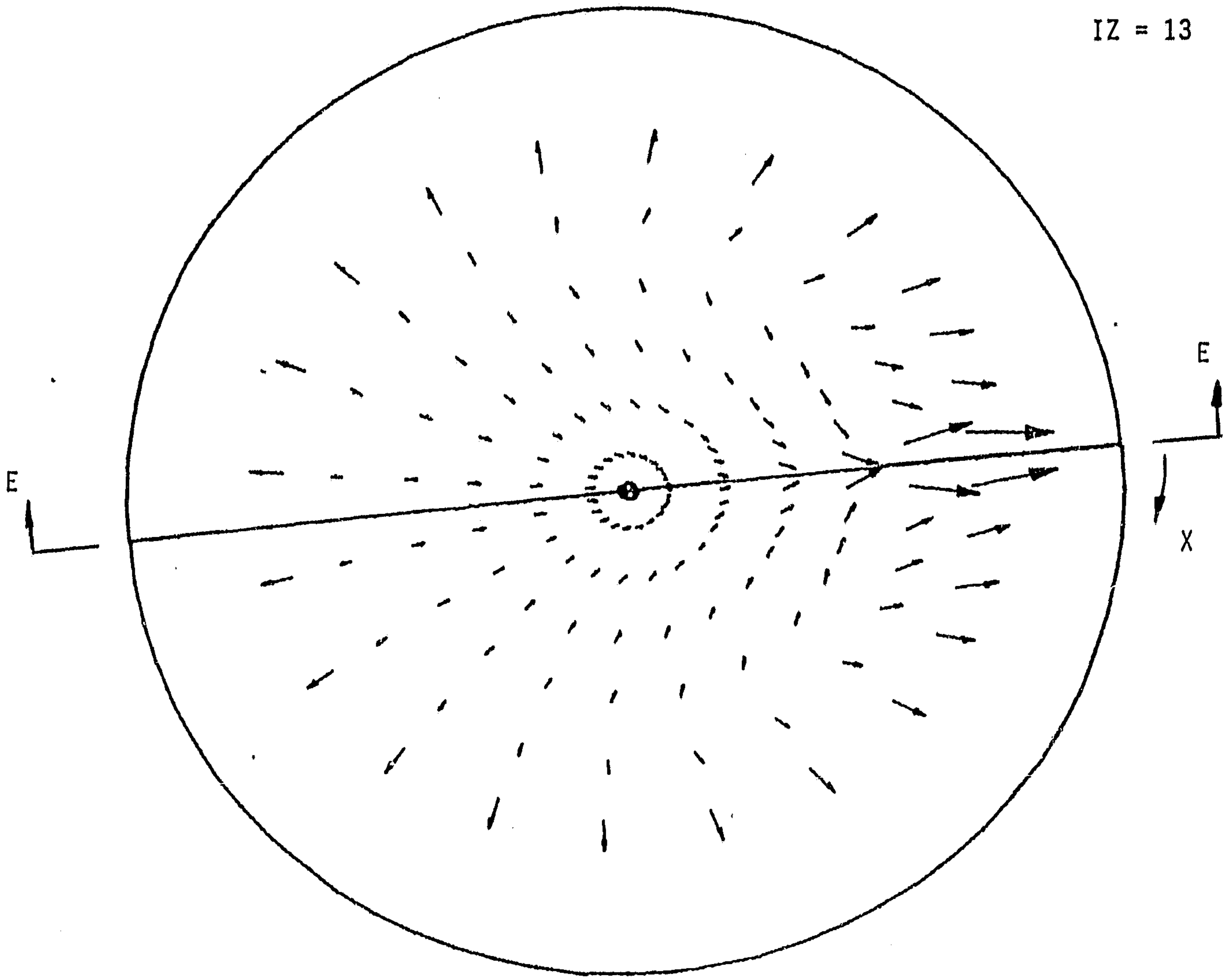


Figure C-2 Velocity Vector Diagrams at t = 12000s

Velocity Vector
VMAX = 0.5 ft/sec

CASE 2

t = 19800s
(5.5 hrs.)



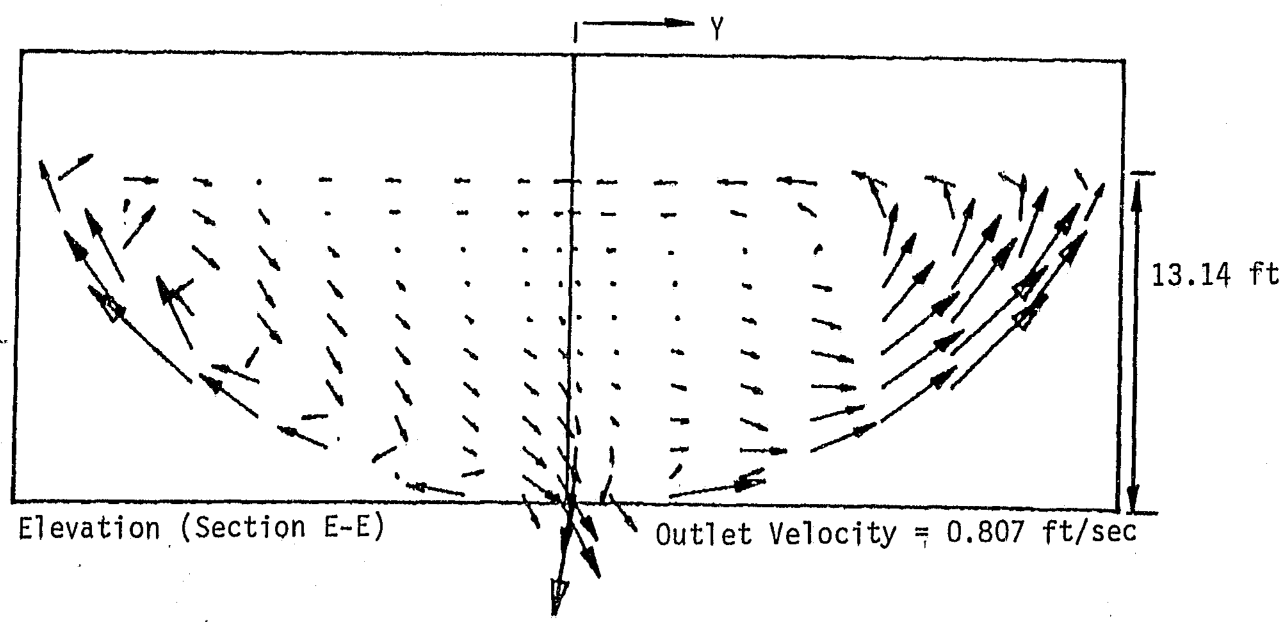


Figure C-3 Velocity Vector Diagrams at t = 19800s

Temperature ^{o}R

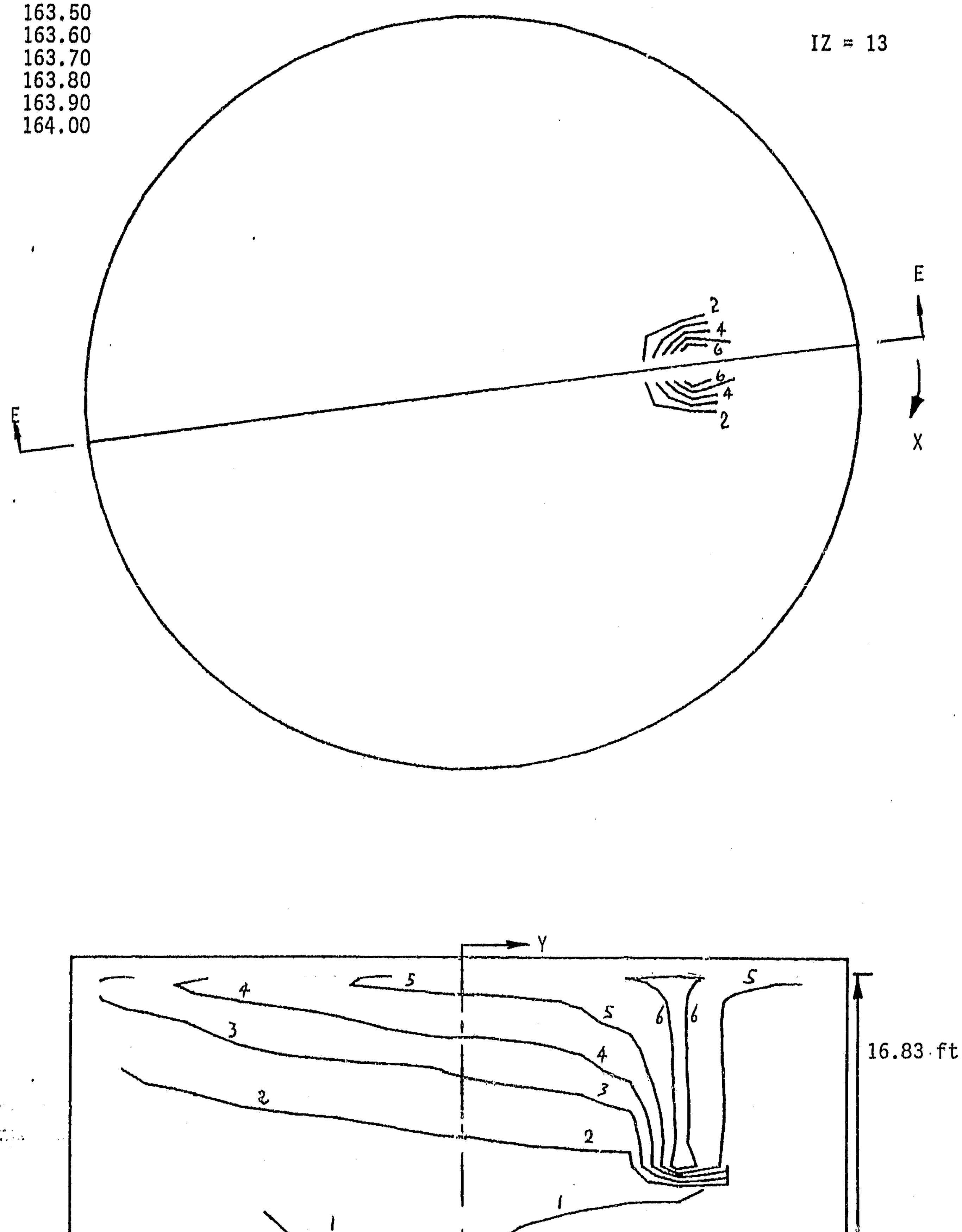
Contours

1 163.50
2 163.60
3 163.70
4 163.80
5 163.90
6 164.00

CASE 2

t = 4000s
(1.11 hrs)

IZ = 13



Elevation (Section E-E)

Figure C-4 Temperature Contours at t = 4000s

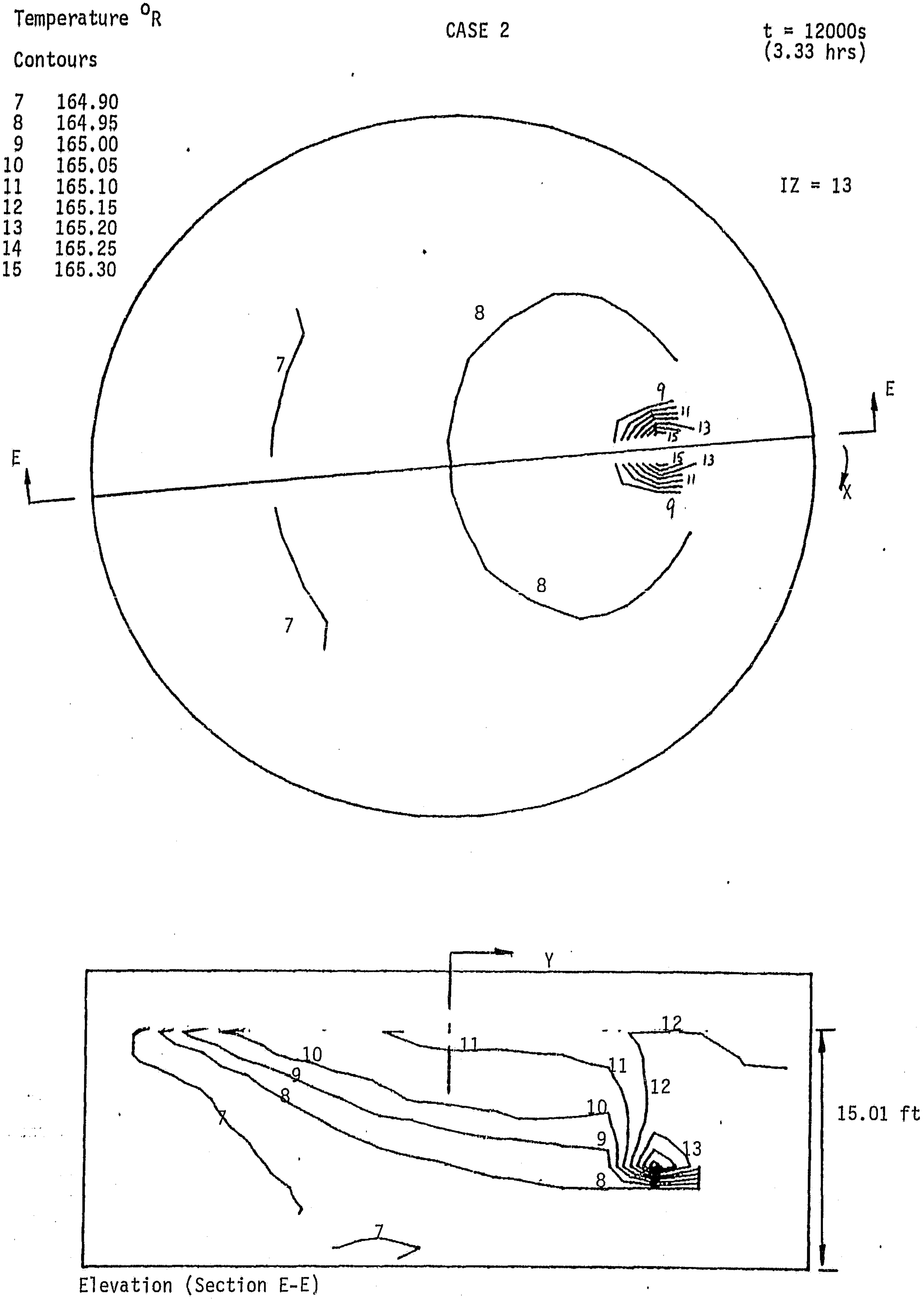


Figure C-5 Temperature Contours at t = 12000s

Temperautre ^{o}R

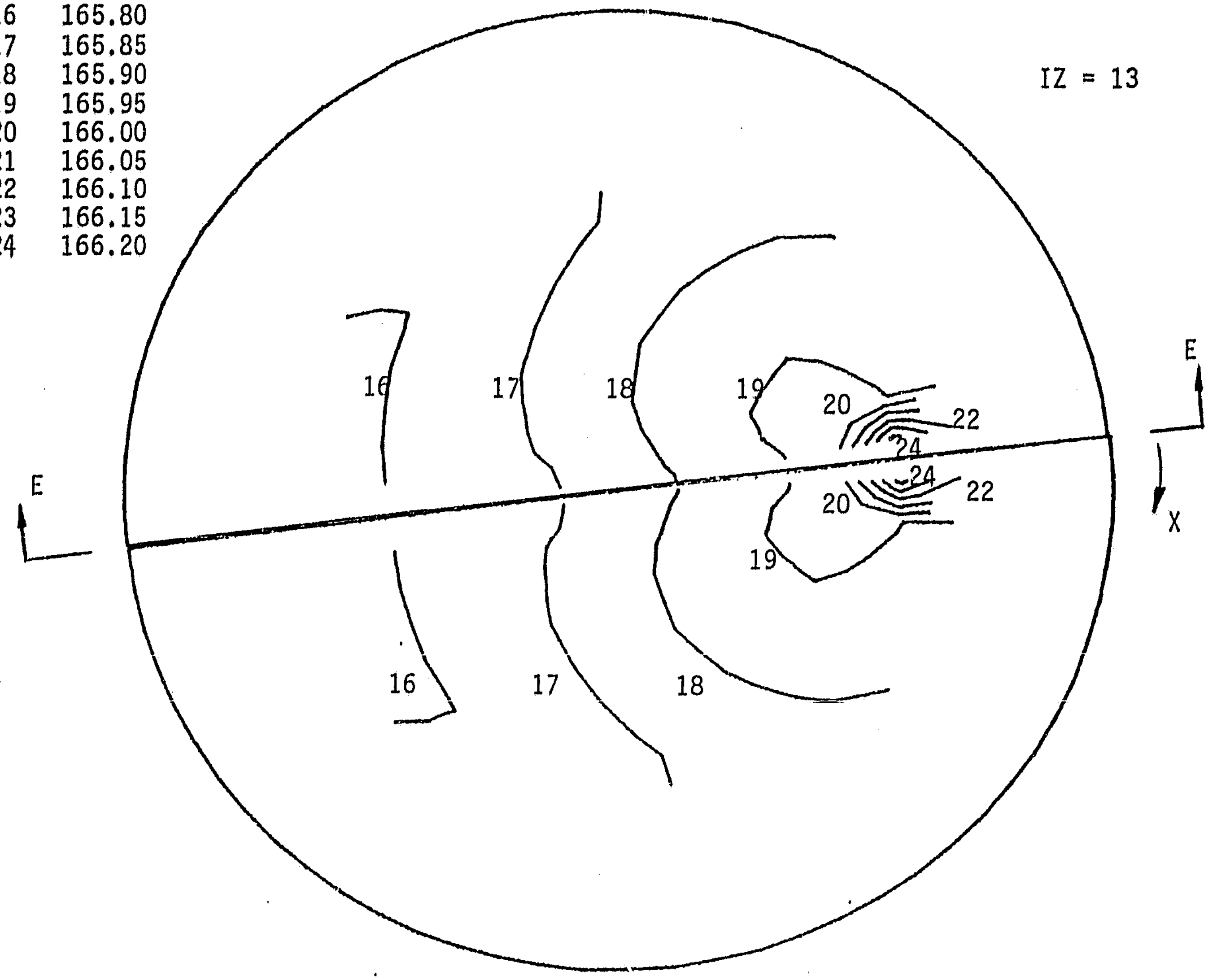
CASE 2

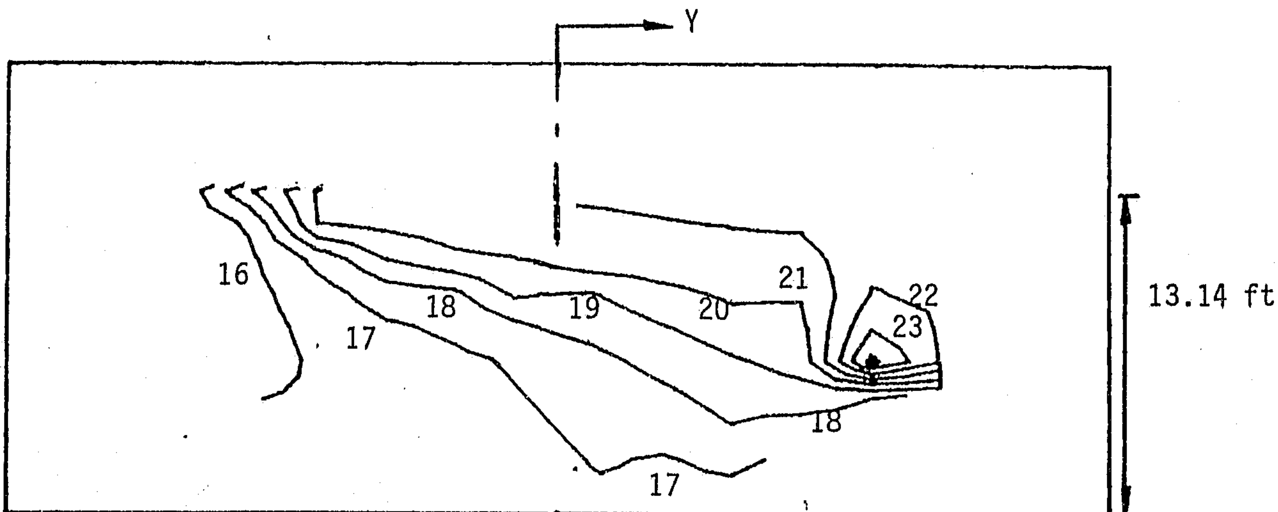
t = 19800s
(5.5 hrs.)

Contours

16	165.80
17	165.85
18	165.90
19	165.95
20	166.00
21	166.05
22	166.10
23	166.15
24	166.20

IZ = 13





Elevation (Section E-E)

Figure C-6 Temperature Contours at t = 19800s

VMAX = 0.39 ft/sec

CASE 2
t = 4000s
(1.11 hrs)

Elevation (Section F-F)

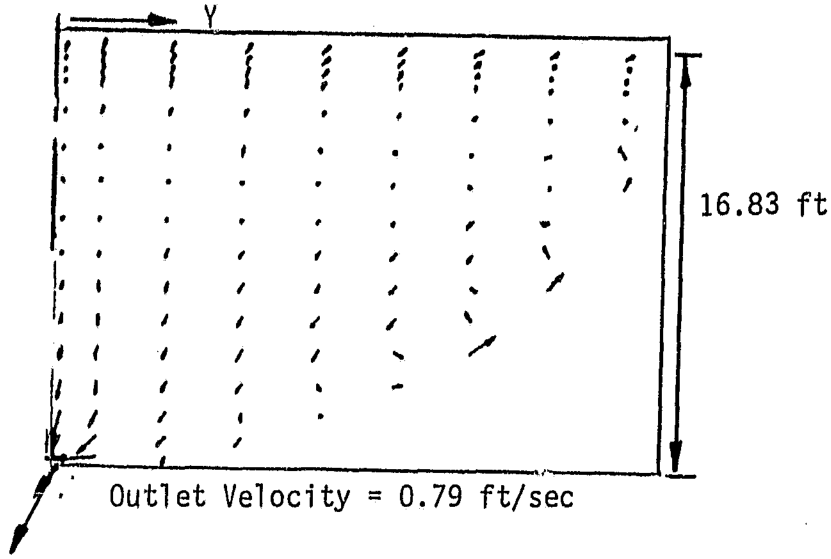


Figure C-7 Velocity Vectors at t = 4000s

Elevation (Section F-F)

CASE 2
t = 4000s
(1.11 hrs)

Temperature ^{o}R

Contours

1	163.50
2	163.60
3	163.70
4	163.80
5	163.90

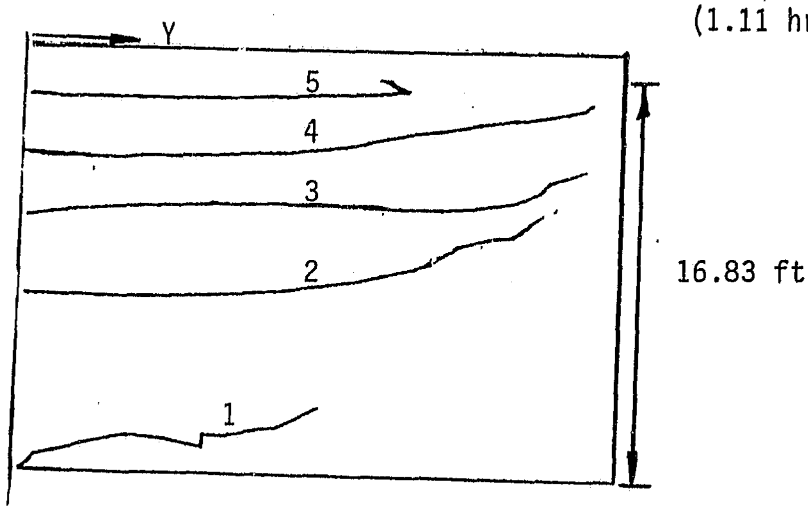


Figure C-8 Temperature Contours at t = 4000s

VMAX = 0.45 ft/sec

Elevation (Section F-F)

CASE 2
t = 12000s
(3.33 hrs)

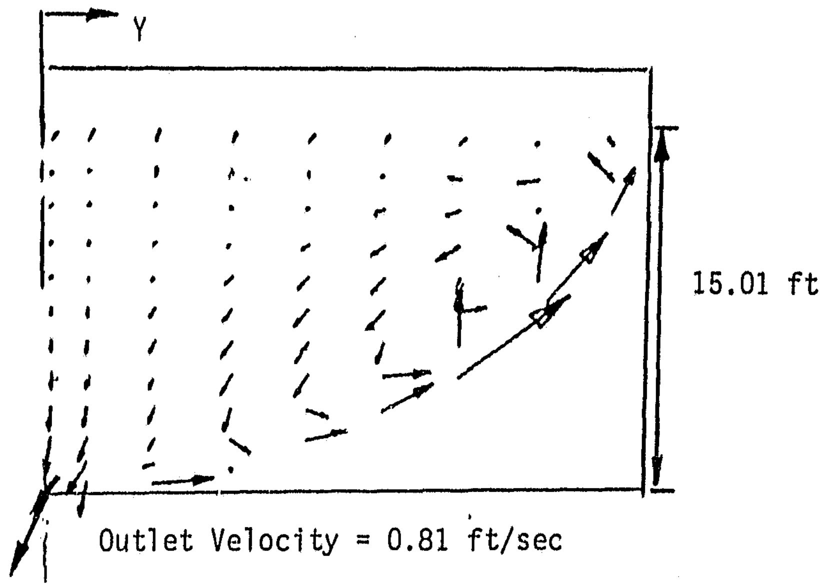


Figure C-9 Velocity Vectors at t = 12000s

Temperature ^{o}R

Contours

7 164.90
8 164.95
9 165.00
10 165.05
11 165.10

Elevation (Section F-F)

CASE 2
t = 12000s
(3.33 hrs)

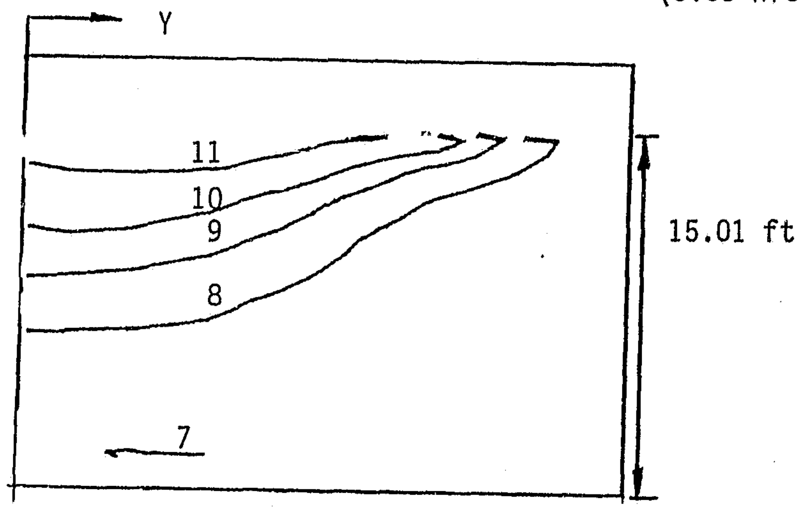


Figure C-10 Temperature Contours at t = 12000s

VMAX = 0.5 ft/sec

Elevation (Section F-F)

CASE 2
t = 19800s
(5.5 hrs.)

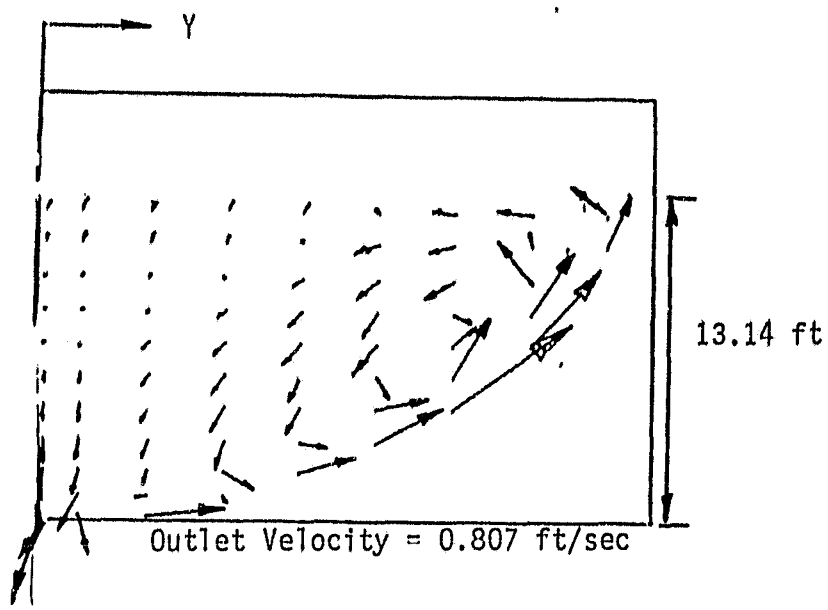


Figure C-11 Velocity Vectors at t = 19800s

Temperature °R

Contours

16 165.80
17 165.85
18 165.90
19 165.95

Elevation (Section F-F)

CASE 2
t = 19800s
(5.5 hrs.)

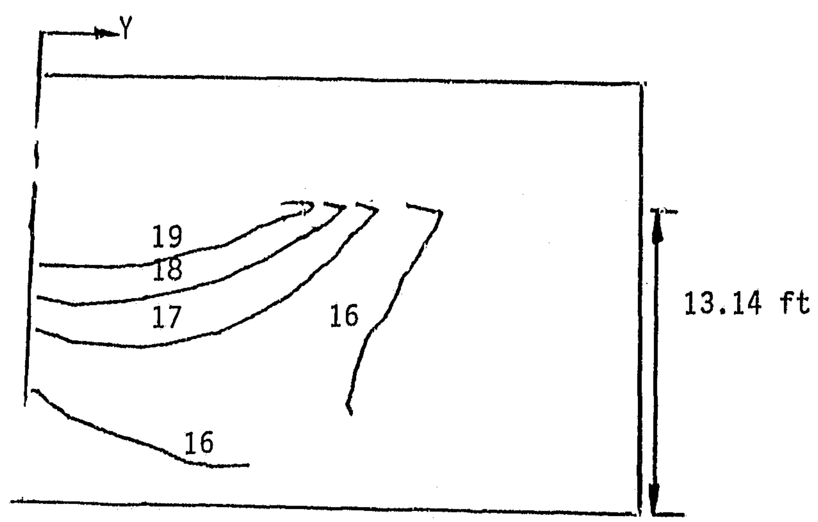


Figure C-12 Temperature Contours at t = 19800s

APPENDIX D

Graphical Results (Velocity Vector Diagrams and Temperature Contours) of Test Case 3

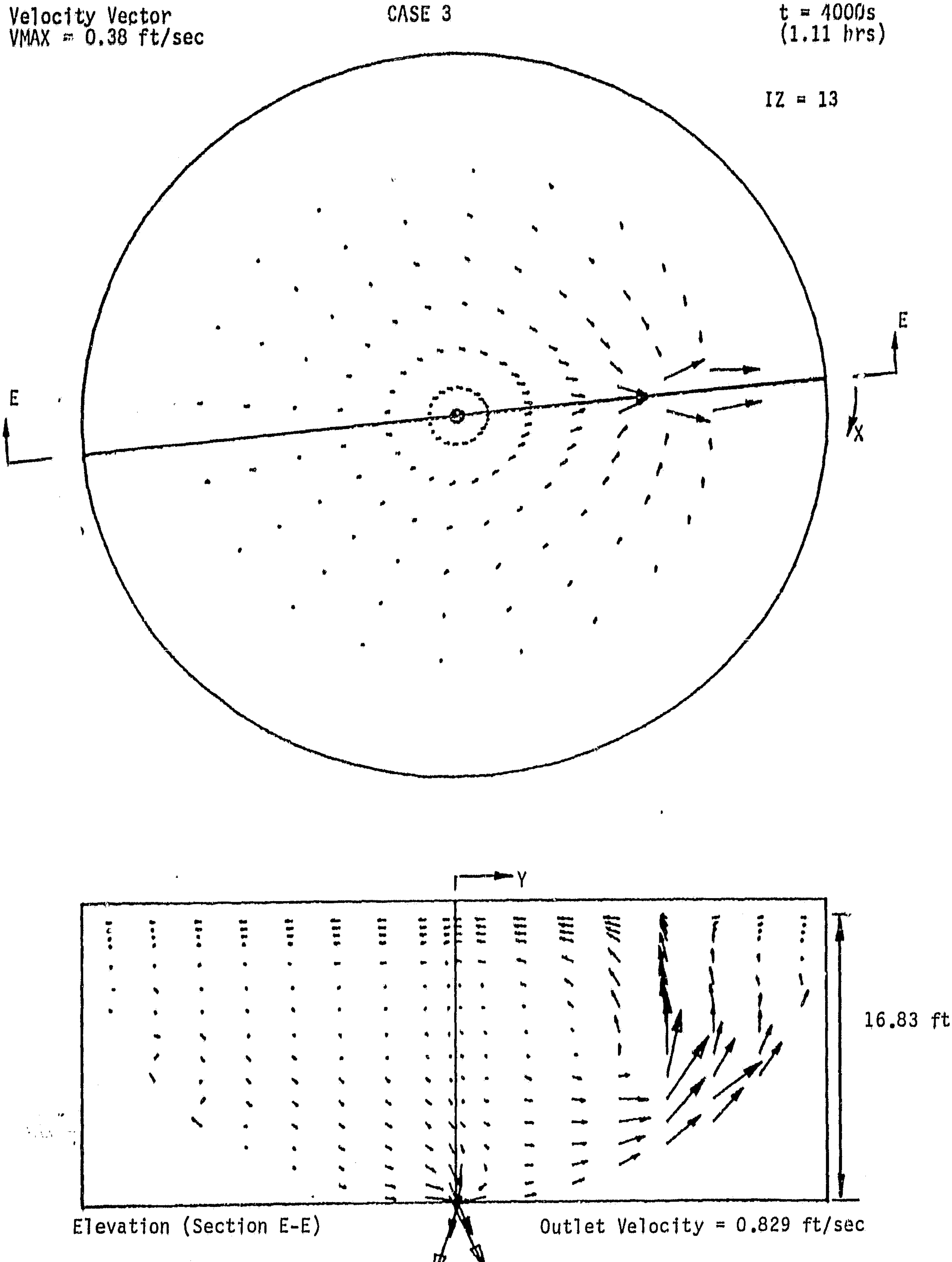


Figure D-1 Velocity Vector Diagrams at t = 4000s

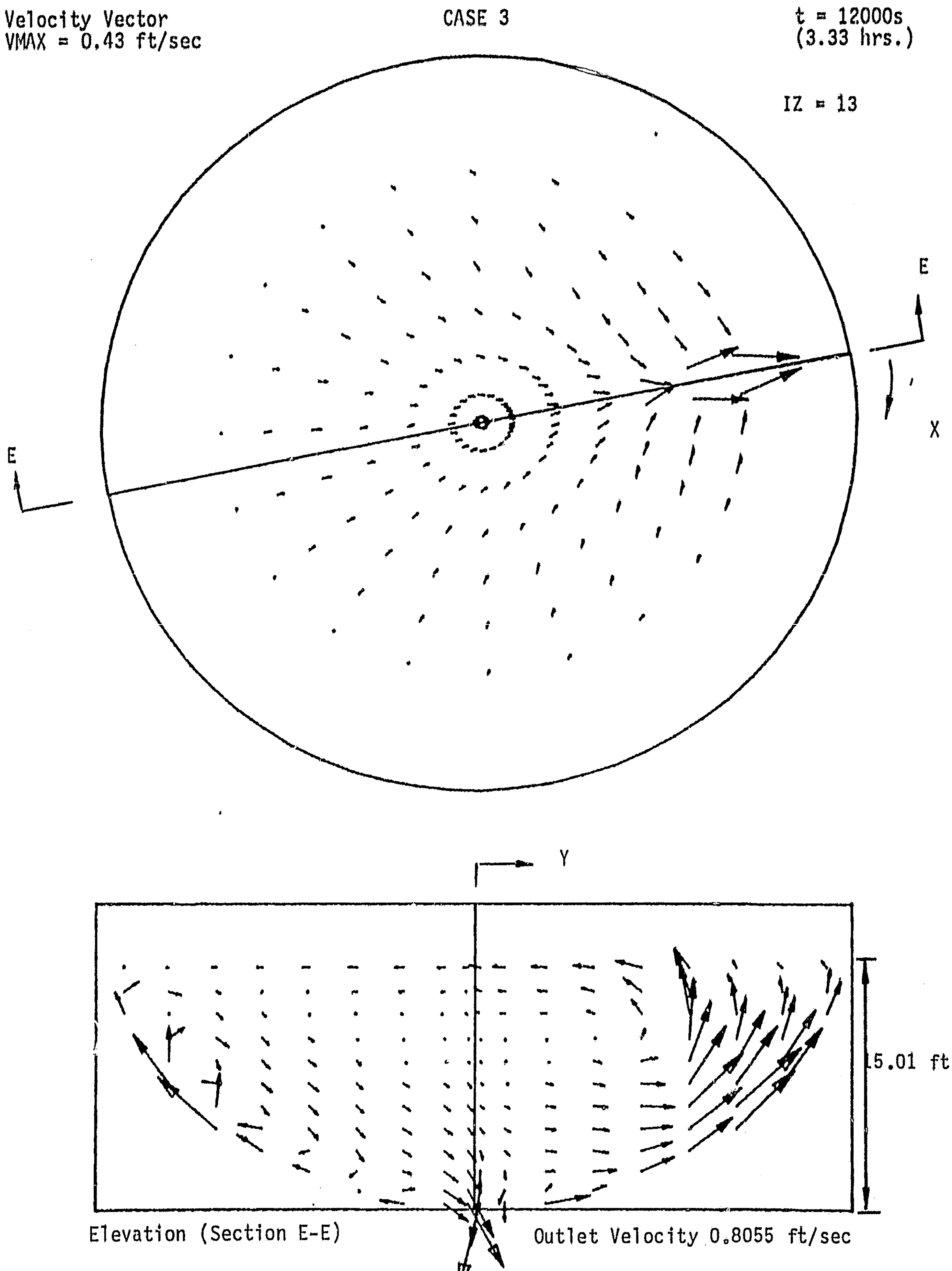


Figure D-2. Velocity Vector Diagrams at t = 12000s

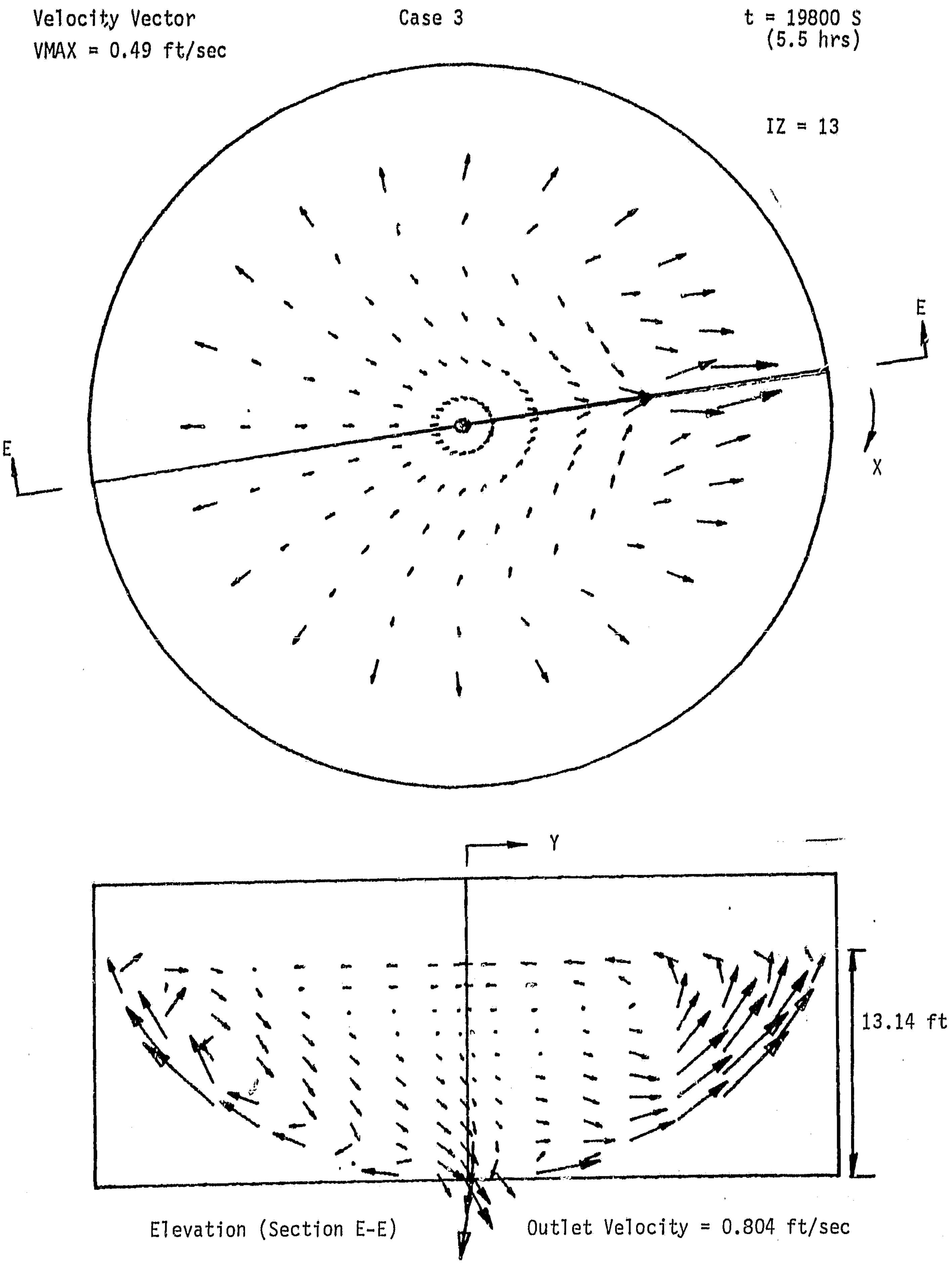


Figure D-3 Velocity Vector Diagrams at t = 19800 S

Temperautre ^oR

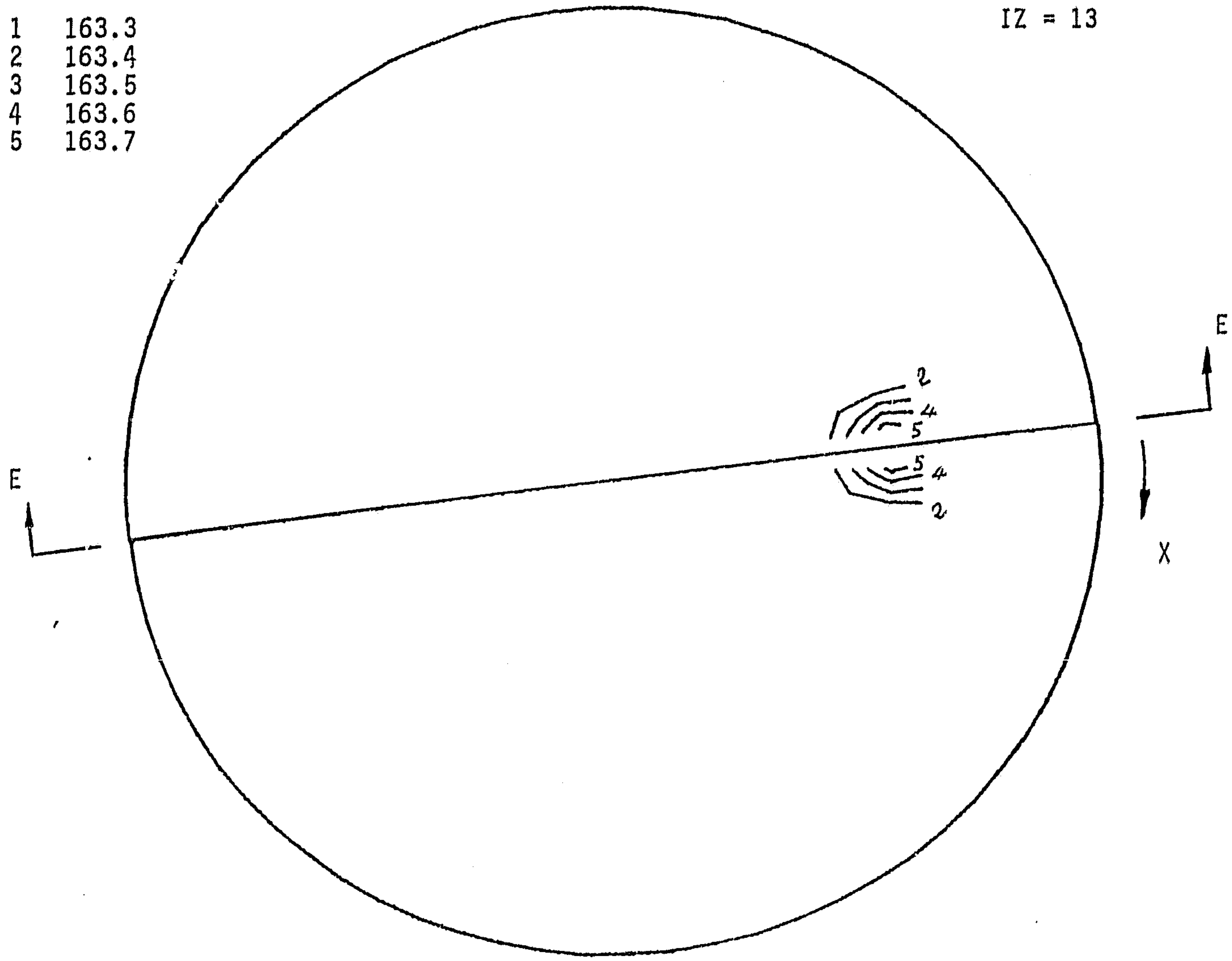
CASE 3

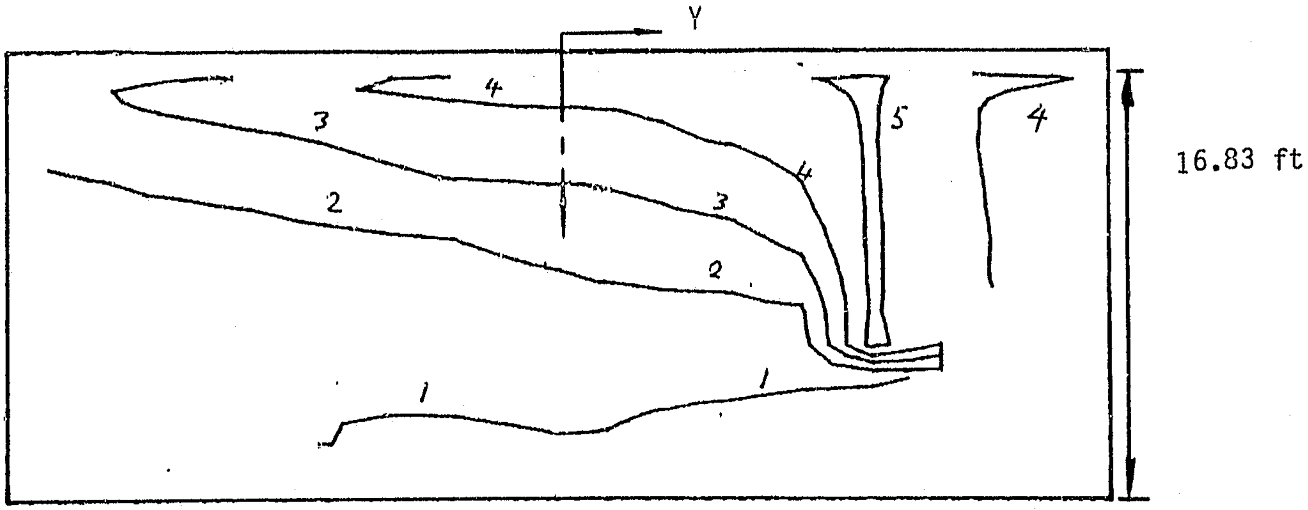
t = 4000s
(1.11 hrs)

Contours

1 163.3
2 163.4
3 163.5
4 163.6
5 163.7

IZ = 13





Elevation (Section E-E)

Figure D-4 Temperature Contours at t = 4000s

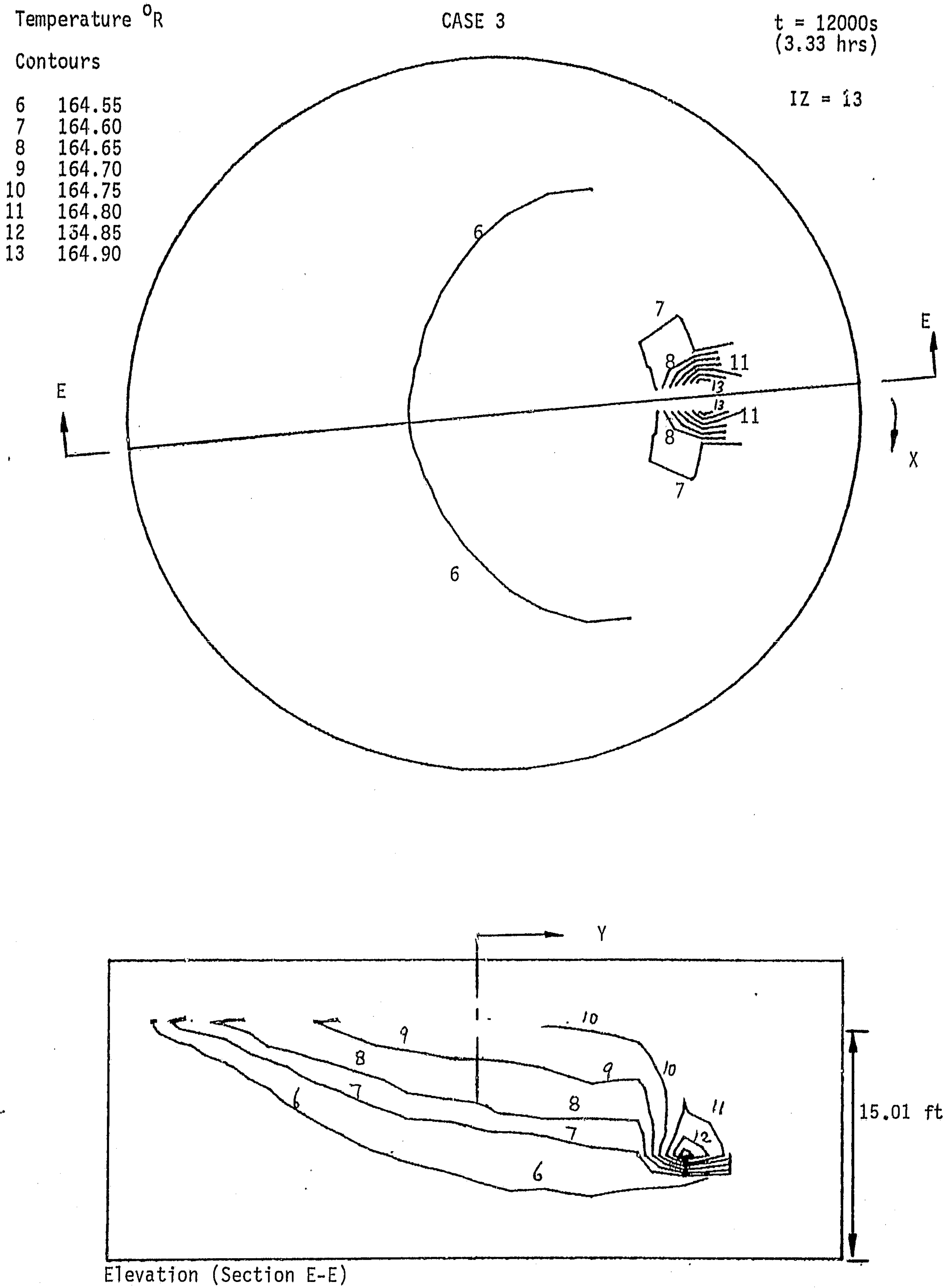
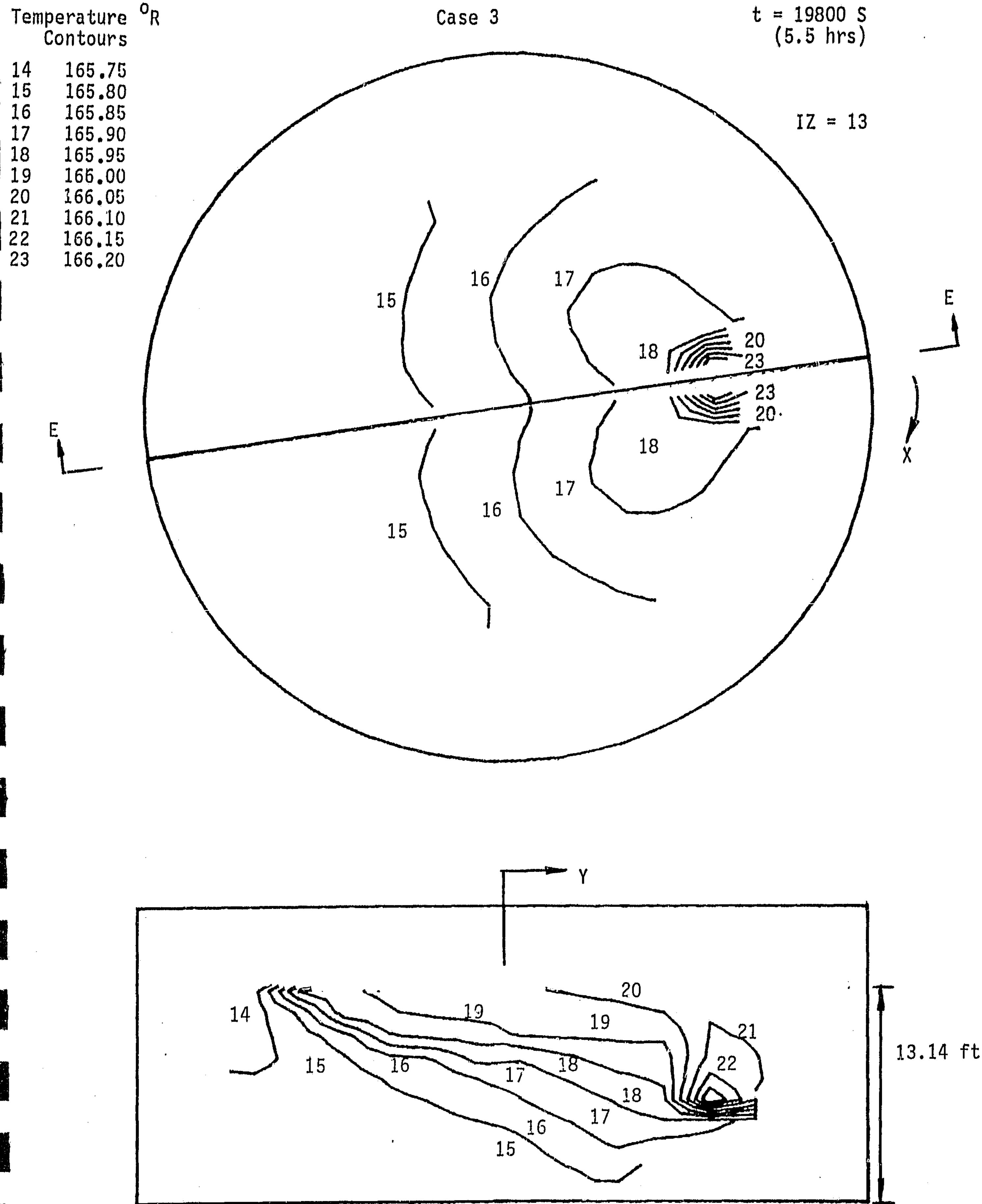


Figure D-5 Temperature Contours at t = 12000s



Elevation (Section E-E)

Figure D-6 Temperature Contours at t = 19800 S

VMAX = 0.38 ft/sec

Elevation (Section F-F)

CASE 3
t = 4000s
(1.11 hrs)

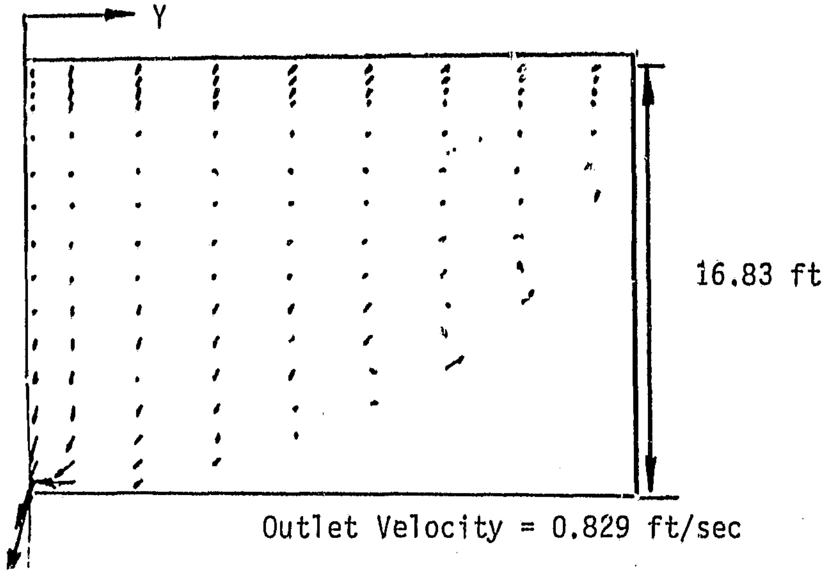


Figure D-7 Velocity Vectors at t = 4000s.

Temperature ^{o}R

Contours

1 163.3
2 163.4
3 163.5
4 163.6

Elevation (Section F-F)

CASE 3
t = 4000s
(1.11 hrs)

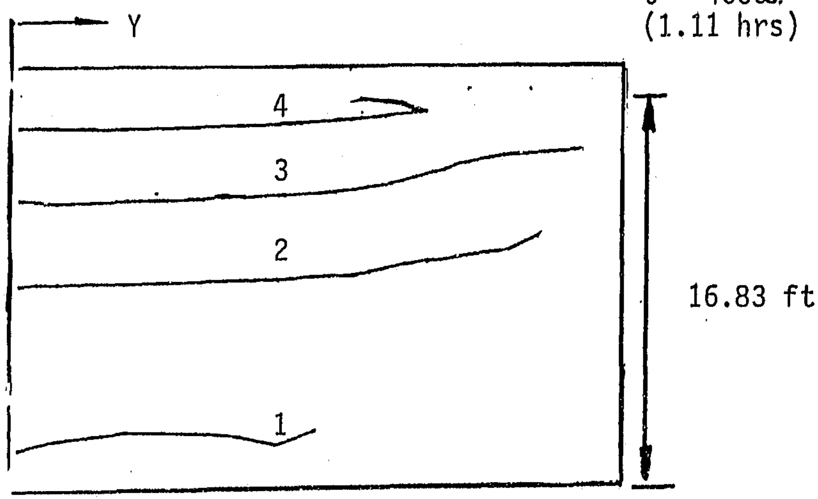


Figure D-8 Temperature Contours at t = 4000s.

VMAX = 0.43 ft/sec

Elevation (Section F-F)

CASE 3
t = 12000s
(3.33 hrs)

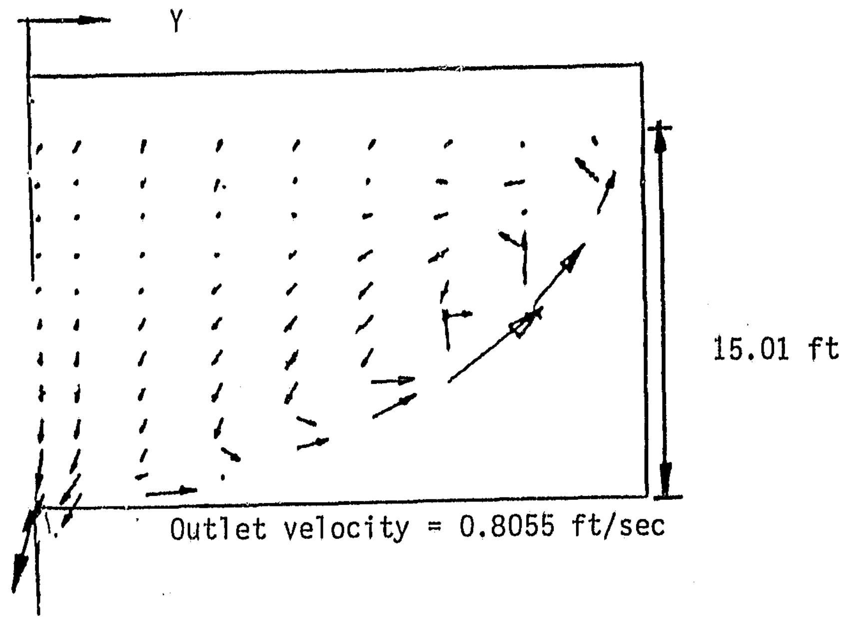


Figure D-9 Velocity Vectors at t = 12000s

Temperature ^{o}R

Contours

6 164.55
7 164.60
8 164.65
9 164.70

Elevation (Section F-F)

CASE 3
t = 12000s
(3.33 hrs)

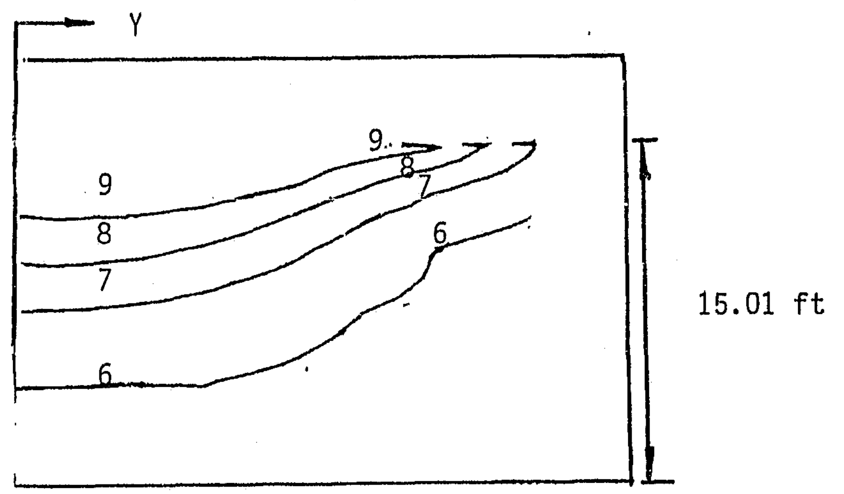


Figure D-10 Temperature Contours at t = 12000s

VMAX = 0.49 ft/sec

Case 3
t = 19800 S
(5.5 hrs)

Elevation (Section F-F)

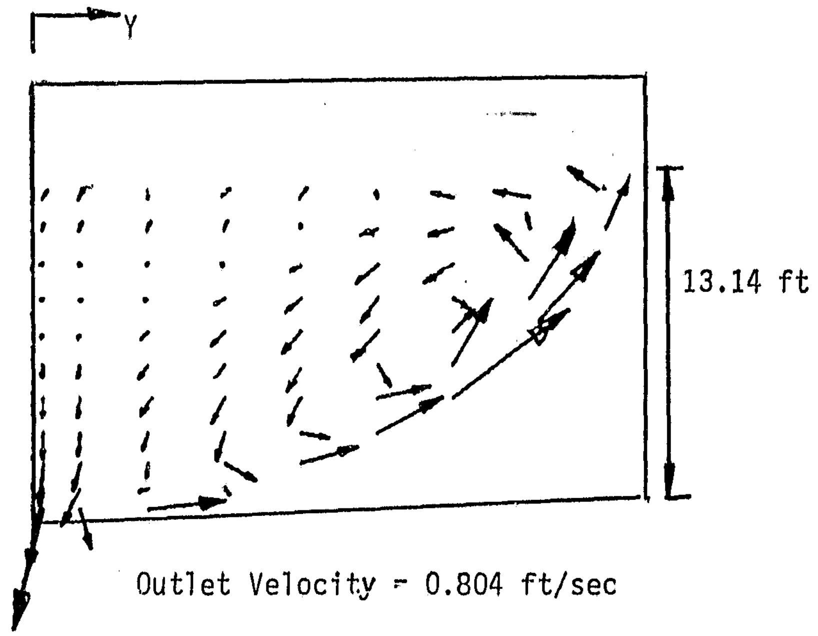


Figure D-11 Belocity Vectors at t = 19800s

Elevation (Section F-F)

Case 3
t = 19800 S
(5.5 hrs)

Temperature ^{o}R

	Contours
15	165.80
16	165.85
17	165.90
18	165.95
19	166.00

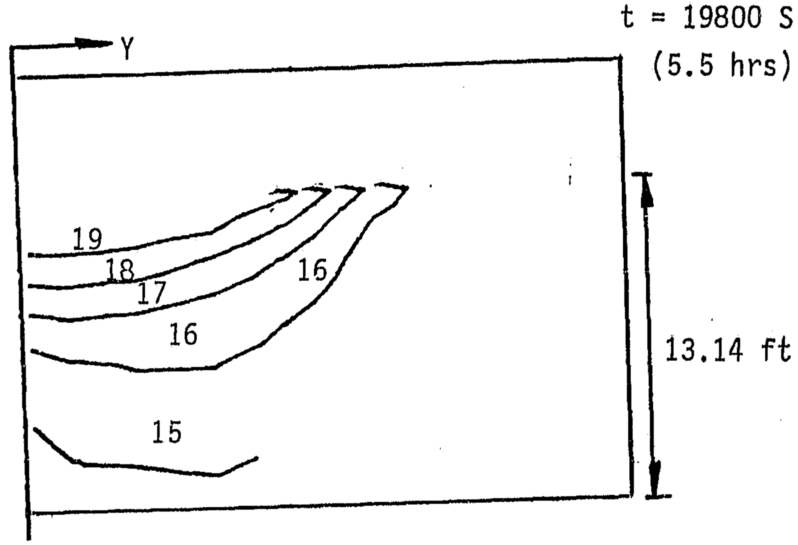


Figure D-12 Temperature Contours at t = 19800s

APPENDIX E

Graphical Results (Velocity Vector Diagrams and Temperature Contours) of Test Case 4

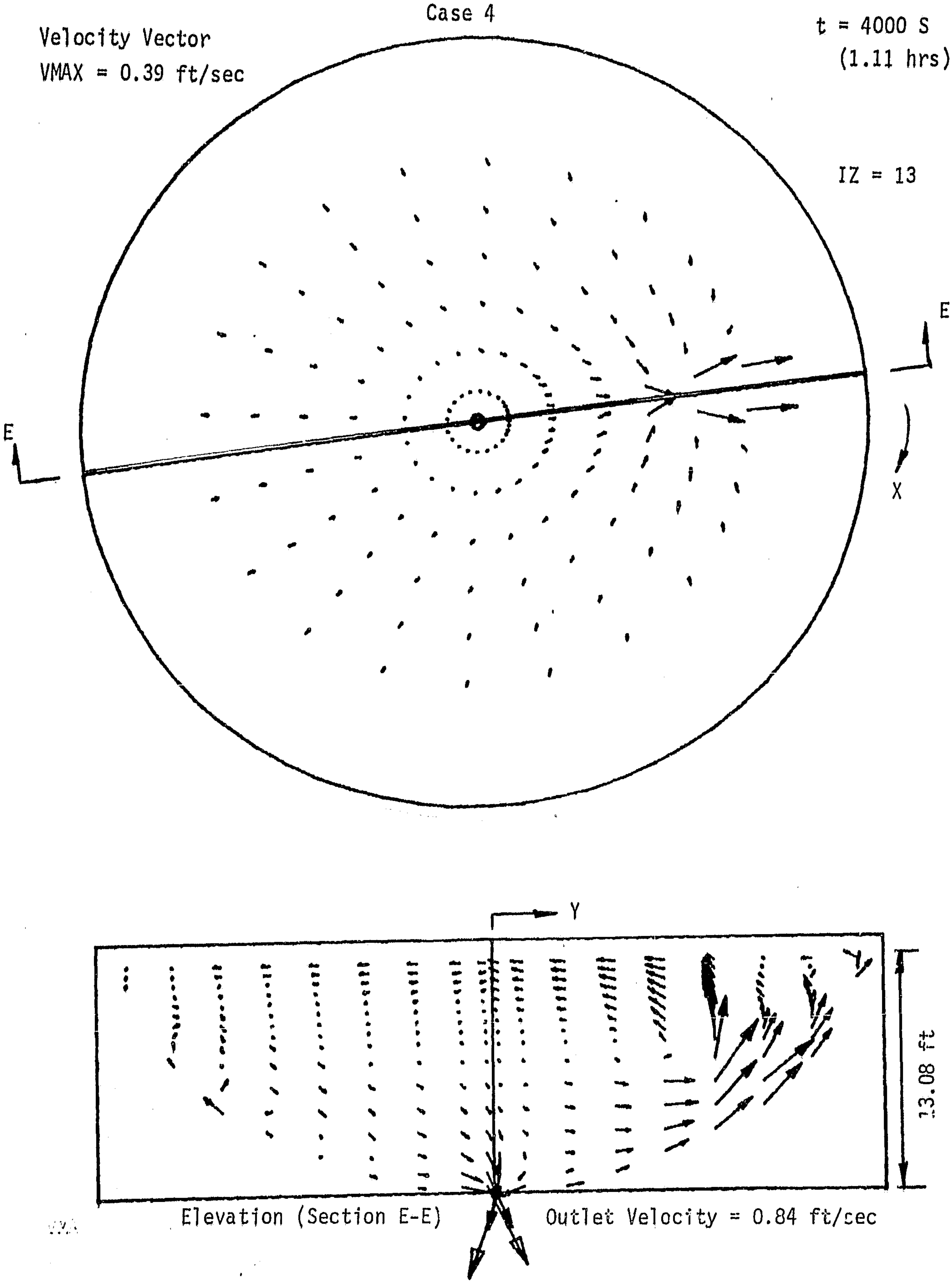


Figure E-1 Velocity Vector Diagram at t = 4000s

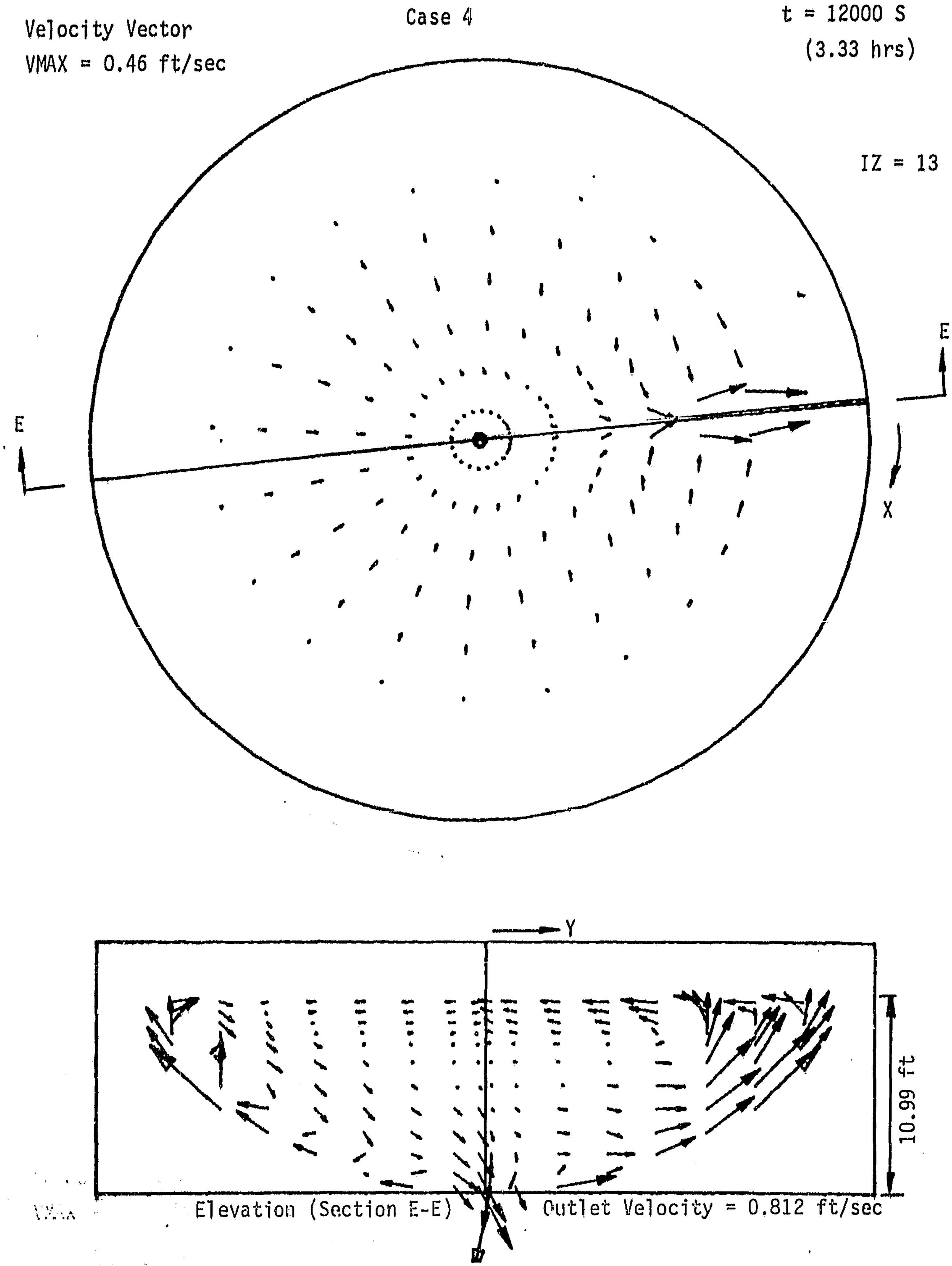


Figure E-2 Velocity Vector Diagrams at t = 12000s

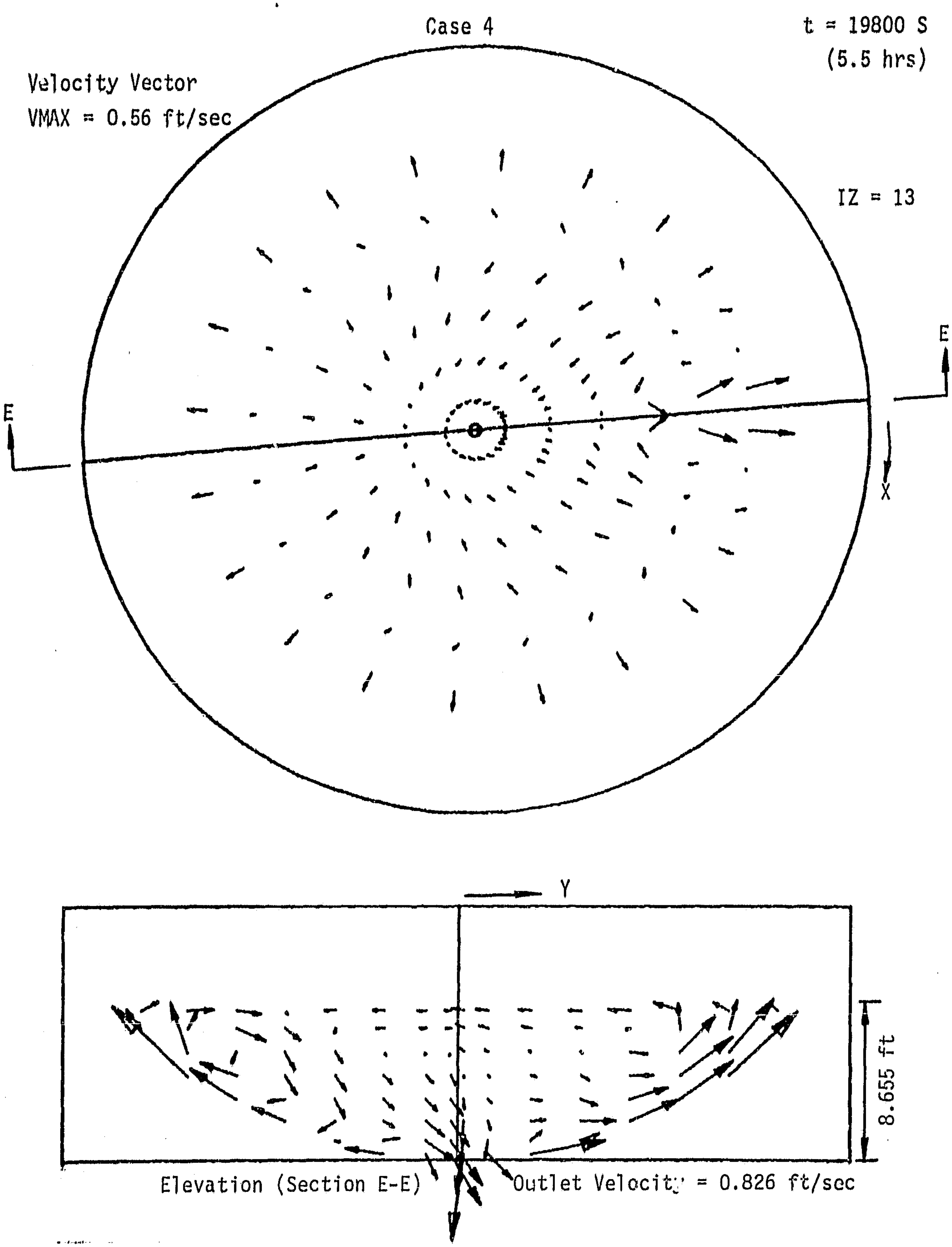


Figure E-3 Velocity Vector Diagrams at t = 19800s

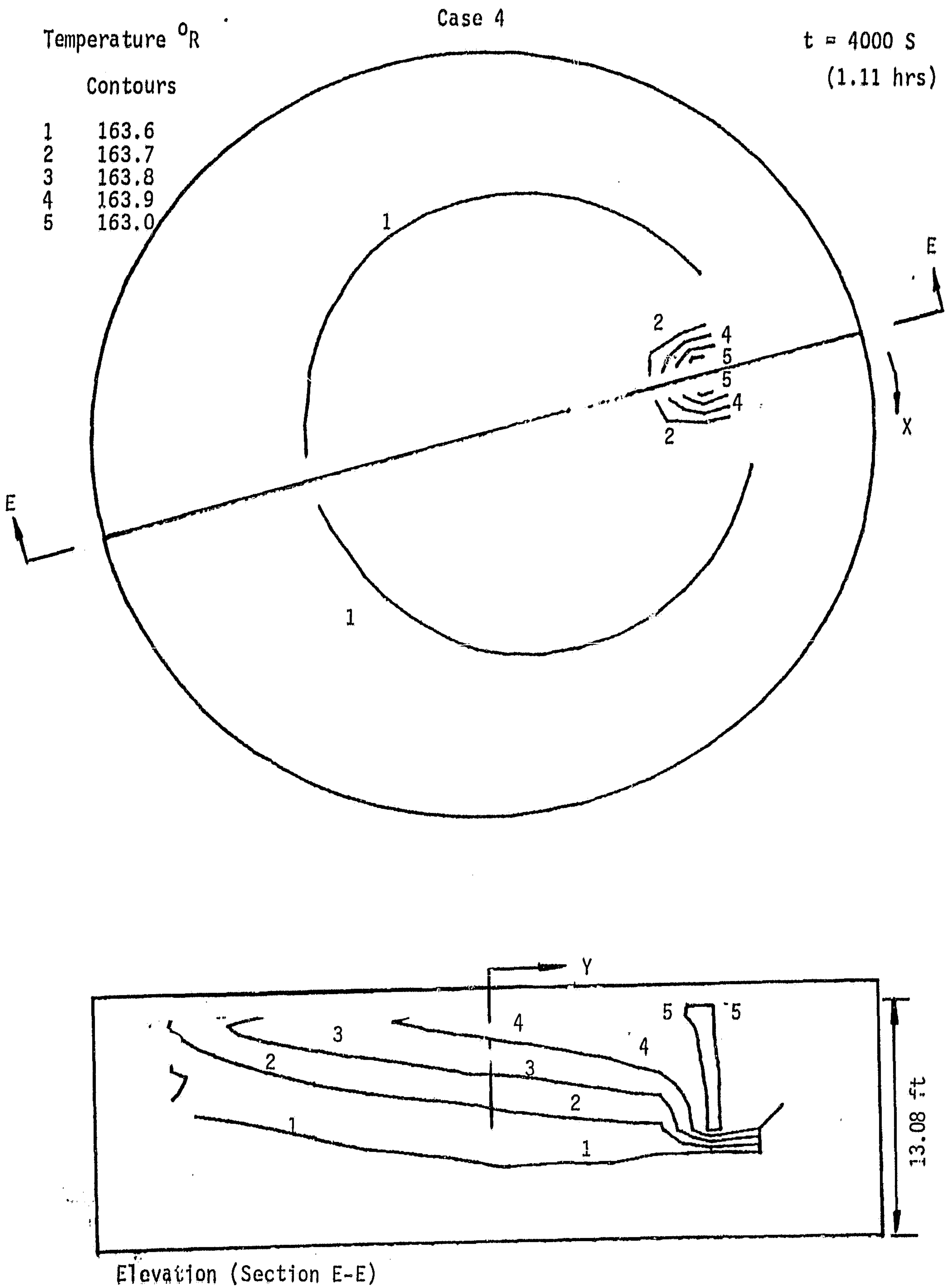
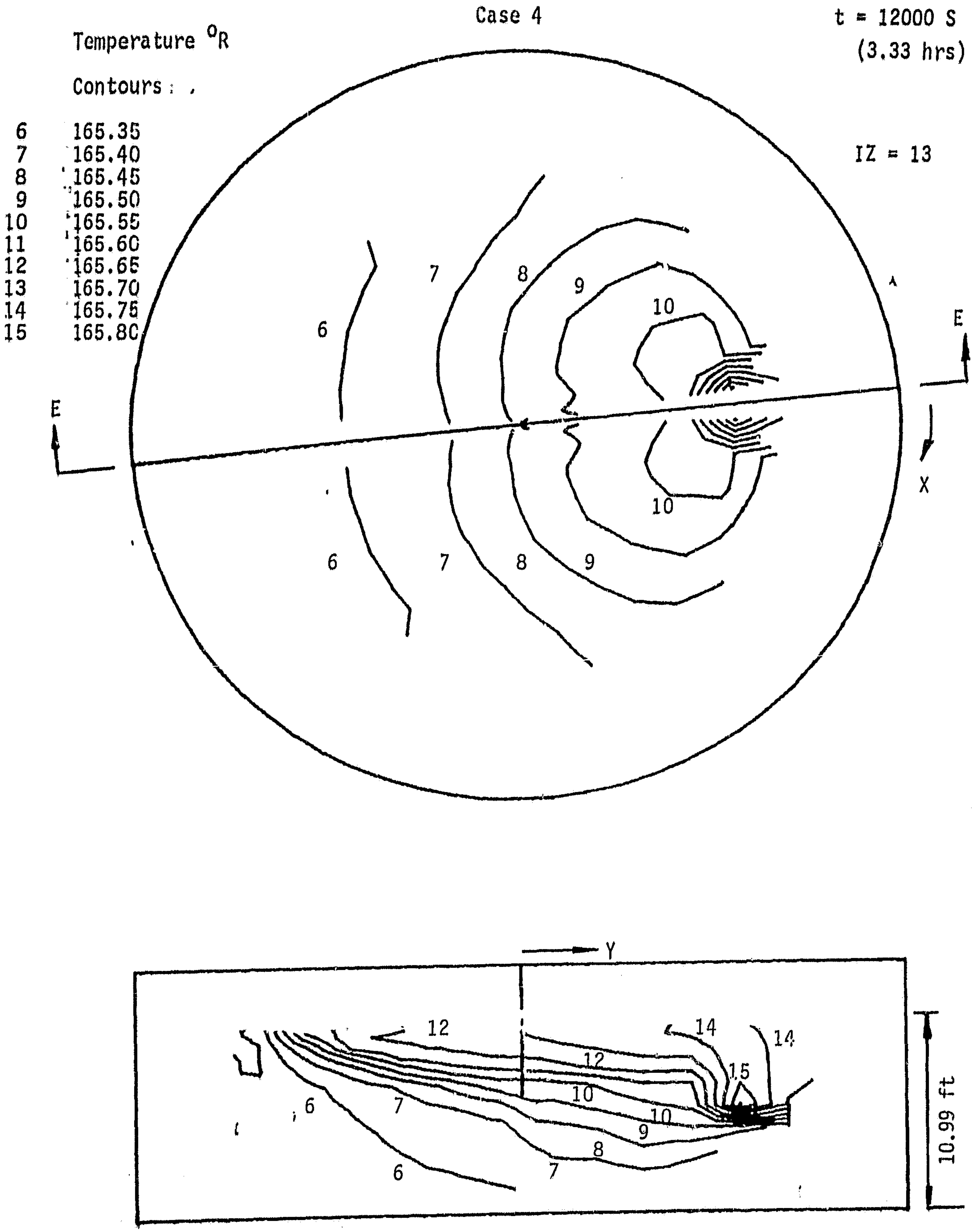


Figure E-4 Temperature Contours at 4000s



Elevation (Section E-E)

Figure E-5 Temperature Contours at t = 12000s

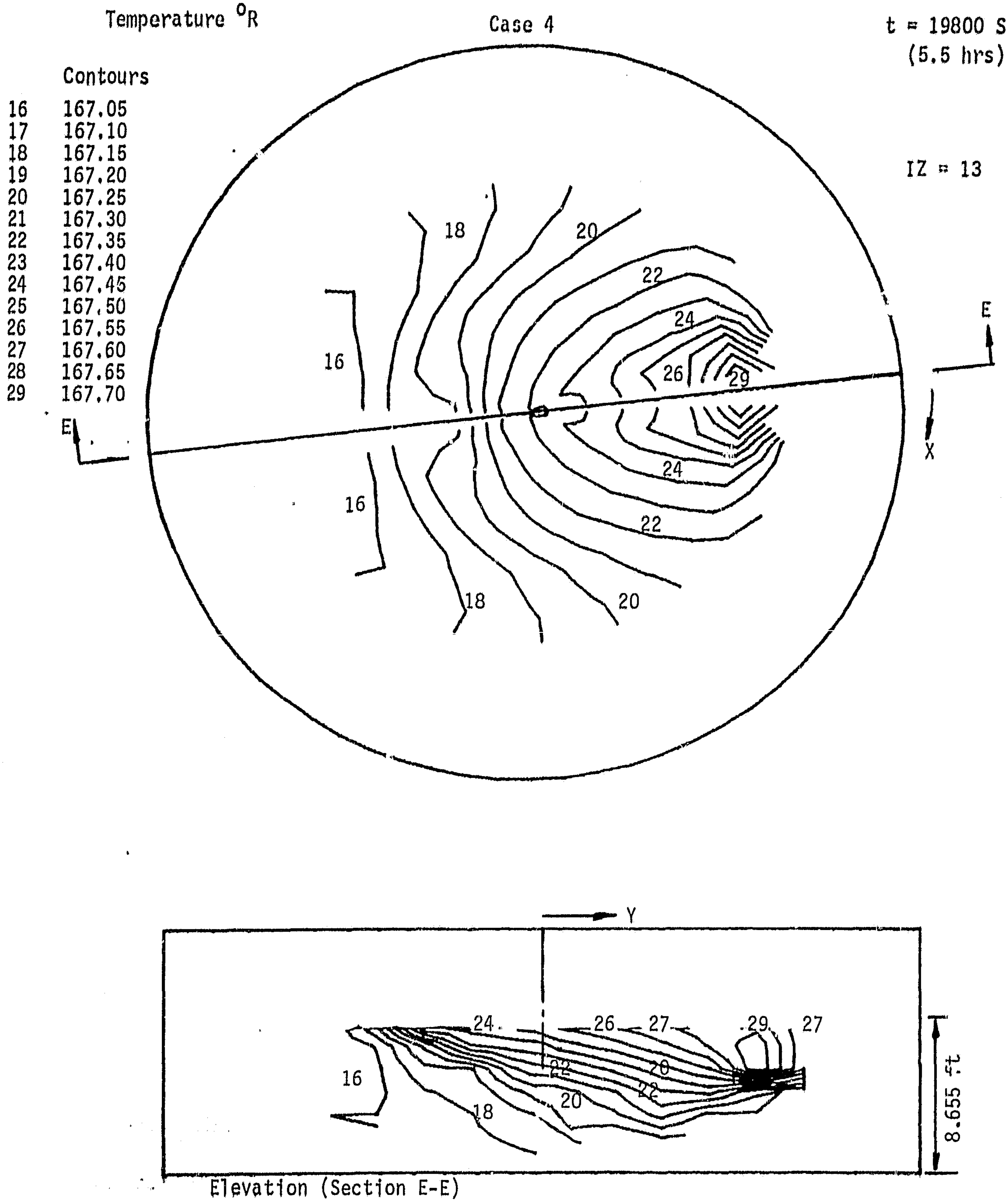


Figure E-6 Temperature Contours at t = 19800s

VMAX = 0 39 ft/sec

Case 4
t = 4000 S
(1.11 hrs)

Elevation (Section F-F)

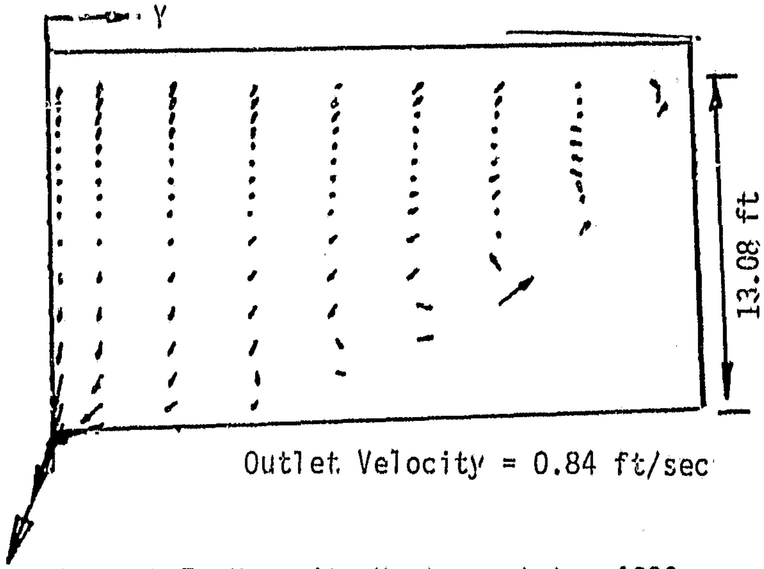


Figure E-7 Velocity Vectors at t = 4000s

Elevation (Section F-F) .

Case 4
t = 4000 S
(1.11 hrs)

Temperature ^{o}R

	Contours
1	163.6
2	163.7
3	163.8
4	163.9

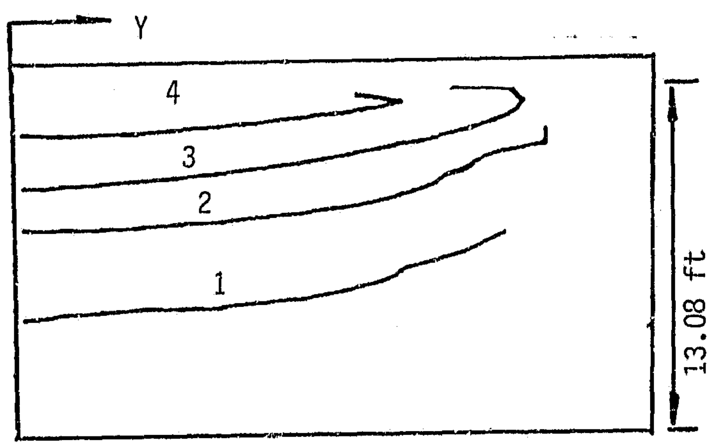


Figure E-8 Temperature Contours at t = 4000s

VMAX = 0.46 ft/sec

Case 4
t = 12000 S
(3.33 hrs)

Elevation (Section F-F)

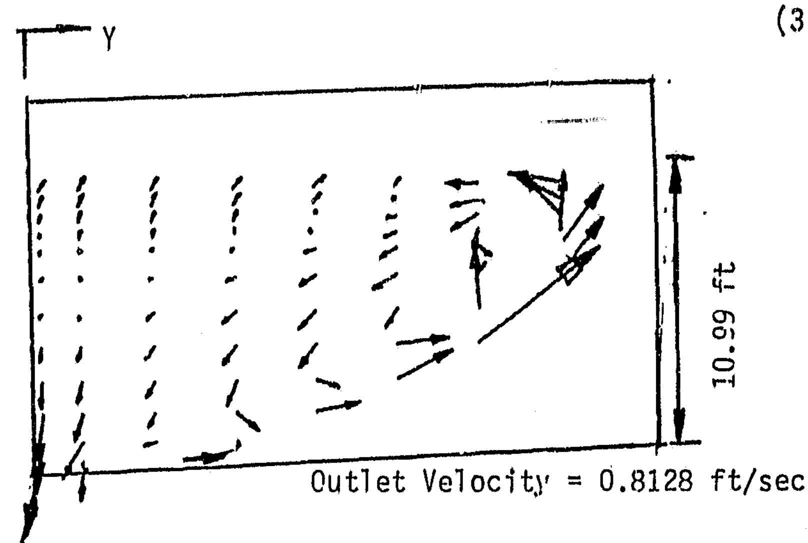


Figure E-9 Velocity Vectors at t = 12000s

Case 4
t = 12000 S
(3.33 hrs)

Elevation (Section F-F)

Temperature ^{o}R

	Contours
6	165.35
7	165.40
8	165.45
9	165.50
10	165.55
11	165.60
12	165.65
13	165.70

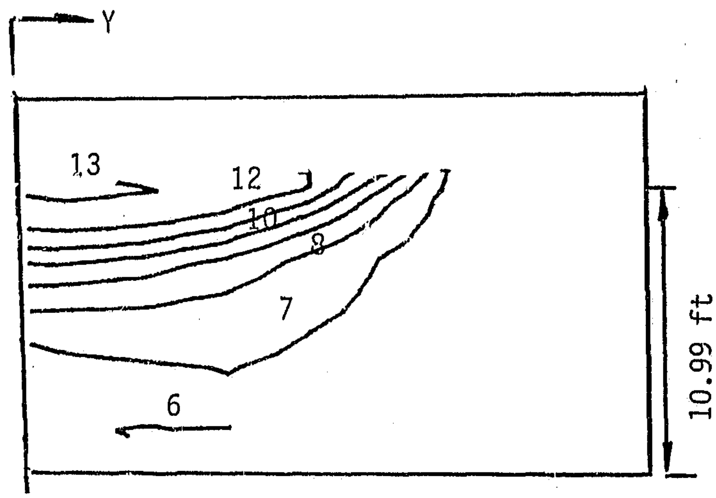


Figure E-10 Temperature Contours at t = 12000s

VMAX = 0.56 ft/sec

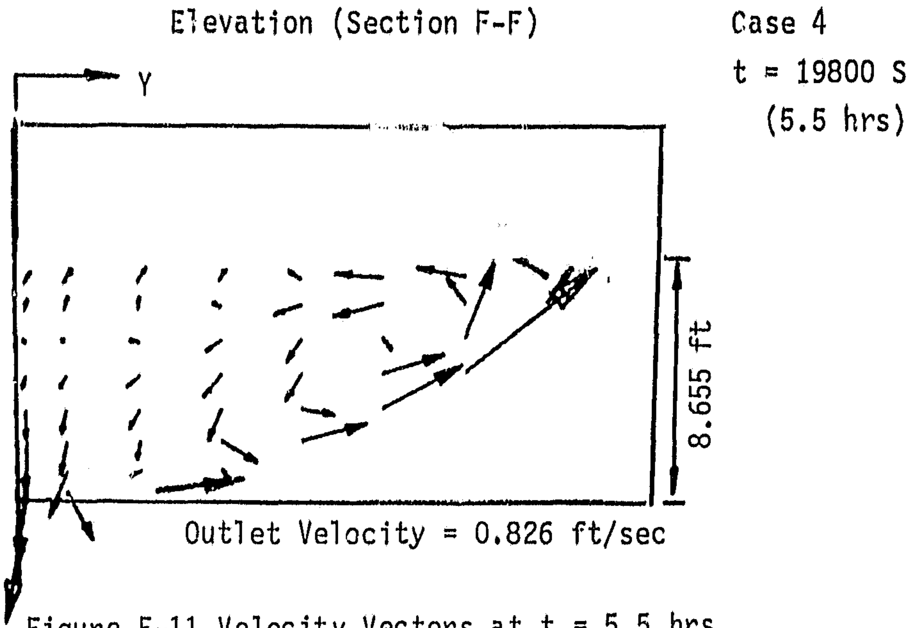


Figure E-11 Velocity Vectors at t = 5.5 hrs

Temperature ^oR

Contours

16	167.05
17	167.10
18	167.15
19	167.20
20	167.25
21	167.30
22	167.35
23	167.40

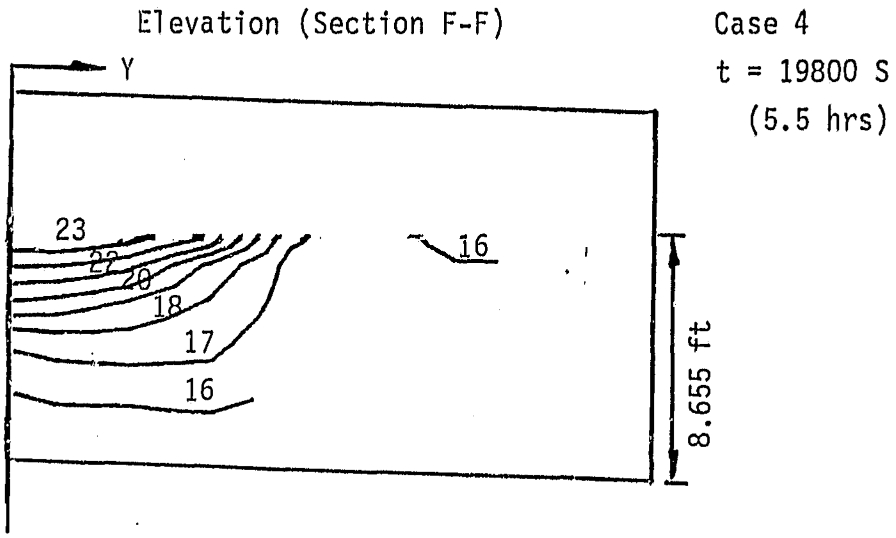


Figure E-12 Temperature Contours at 19800s

APPENDIX F

Global Parameters Printouts of Test Case 1

```
MASS  INFLOW RATE   (LBM/S)      =  6,127E+01
CALCULATED OUTFLOW  (LBM/S)      = -8,352E+01
TOTAL MASS OF LOX   (LBM  )      =  1,030E+06
TOTAL LOX VOLUME    (FT**3)      =  1,450E+04        t = 2000s
TOTAL MASS*ENTH     (BTU  )      =  6,830E+07
AVERAGE DENSITY (LBM/FT**3)      =  7,104E+01
AVERAGE TEMPERATURE (  R )       =  1,633E+02

MASS  INFLOW RATE   (LBM/S)      =  6,125E+01
CALCULATED OUTFLOW  (LBM/S)      = -8,141E+01
TOTAL MASS OF LOX   (LBM  )      =  9,866E+05
TOTAL LOX VOLUME    (FT**3)      =  1,390E+04        t = 4000s
TOTAL MASS*ENTH     (BTU  )      =  6,558E+07
AVERAGE DENSITY (LBM/FT**3)      =  7,098E+01
AVERAGE TEMPERATURE (  R )       =  1,637E+02

MASS  INFLOW RATE   (LBM/S)      =  6,124E+01
CALCULATED OUTFLOW  (LBM/S)      = -8,122E+01
TOTAL MASS OF LOX   (LBM  )      =  9,431E+05
TOTAL LOX VOLUME    (FT**3)      =  1,330E+04        t = 6000s
TOTAL MASS*ENTH     (BTU  )      =  6,284E+07
AVERAGE DENSITY (LBM/FT**3)      =  7,092E+01
AVERAGE TEMPERATURE (  R )       =  1,640E+02

MASS  INFLOW RATE   (LBM/S)      =  6,122E+01
CALCULATED OUTFLOW  (LBM/S)      = -8,103E+01
TOTAL MASS OF LOX   (LBM  )      =  8,997E+05
TOTAL LOX VOLUME    (FT**3)      =  1,270E+04        t = 8000s
TOTAL MASS*ENTH     (BTU  )      =  6,009E+07
AVERAGE DENSITY (LBM/FT**3)      =  7,086E+01
AVERAGE TEMPERATURE (  R )       =  1,644E+02

MASS  INFLOW RATE   (LBM/S)      =  6,120E+01
CALCULATED OUTFLOW  (LBM/S)      = -8,091E+01
TOTAL MASS OF LOX   (LBM  )      =  8,564E+05
TOTAL LOX VOLUME    (FT**3)      =  1,209E+04        t = 10000s
TOTAL MASS*ENTH     (BTU  )      =  5,732E+07
AVERAGE DENSITY (LBM/FT**3)      =  7,081E+01
AVERAGE TEMPERATURE (  R )       =  1,647E+02

MASS  INFLOW RATE   (LBM/S)      =  6,118E+01
CALCULATED OUTFLOW  (LBM/S)      = -8,097E+01
TOTAL MASS OF LOX   (LBM  )      =  8,132E+05
TOTAL LOX VOLUME    (FT**3)      =  1,149E+04        t = 12000s
TOTAL MASS*ENTH     (BTU  )      =  5,454E+07
AVERAGE DENSITY (LBM/FT**3)      =  7,076E+01
AVERAGE TEMPERATURE (  R )       =  1,650E+02
```

Table F-1

Global Quantities printout, for whole LOX Tank - Case 1

(British Units)

```
MASS  INFLOW  RATE     (KG/S)   =   2.779E+01
CALCULATED OUTFLOW     (KG/S)   =  -3.708E+01
TOTAL MASS OF LOX      (KG   )  =   4.672E+05
TOTAL LOX VOLUME       (M**3)   =   4.106E+02
TOTAL MASS*ENTH      (JOULES)   =   7.201E+10
AVERAGE DENSITY (KG/M**3    )   =   1.138E+03
AVERAGE TEMPERATURE    (  K )   =   9.072E+01
```

t = 2000s

```
MASS  INFLOW  RATE     (KG/S)   =   2.778E+01
CALCULATED OUTFLOW     (KG/S)   =  -3.692E+01
TOTAL MASS OF LOX      (KG   )  =   4.474E+05
TOTAL LOX VOLUME       (M**3)   =   3.936E+02
TOTAL MASS*ENTH      (JOULES)   =   6.913E+10
AVERAGE DENSITY (KG/M**3    )   =   1.137E+03
AVERAGE TEMPERATURE    (  K )   =   9.094E+01
```

t = 4000s

```
MASS  INFLOW  RATE     (KG/S)   =   2.777E+01
CALCULATED OUTFLOW     (KG/S)   =  -3.683E+01
TOTAL MASS OF LOX      (KG   )  =   4.277E+05
TOTAL LOX VOLUME       (M**3)   =   3.766E+02
TOTAL MASS*ENTH      (JOULES)   =   6.625E+10
AVERAGE DENSITY (KG/M**3    )   =   1.136E+03
AVERAGE TEMPERATURE    (  K )   =   9.113E+01
```

t = 6000s

```
MASS  INFLOW  RATE     (KG/S)   =   2.776E+01
CALCULATED OUTFLOW     (KG/S)   =  -3.675E+01
TOTAL MASS OF LOX      (KG   )  =   4.080E+05
TOTAL LOX VOLUME       (M**3)   =   3.595E+02
TOTAL MASS*ENTH      (JOULES)   =   6.334E+10
AVERAGE DENSITY (KG/M**3    )   =   1.135E+03
AVERAGE TEMPERATURE    (  K )   =   9.132E+01
```

t = 8000s

```
MASS  INFLOW  RATE     (KG/S)   =   2.775E+01
CALCULATED OUTFLOW     (KG/S)   =  -3.669E+01
TOTAL MASS OF LOX      (KG   )  =   3.884E+05
TOTAL LOX VOLUME       (M**3)   =   3.425E+02
TOTAL MASS*ENTH      (JOULES)   =   6.042E+10
AVERAGE DENSITY (KG/M**3    )   =   1.134E+03
AVERAGE TEMPERATURE    (  K )   =   9.149E+01
```

t = 10000s

```
MASS  INFLOW  RATE     (KG/S)   =   2.774E+01
CALCULATED OUTFLOW     (KG/S)   =  -3.672E+01
TOTAL MASS OF LOX      (KG   )  =   3.688E+05
TOTAL LOX VOLUME       (M**3)   =   3.255E+02
TOTAL MASS*ENTH      (JOULES)   =   5.749E+10
AVERAGE DENSITY (KG/M**3    )   =   1.133E+03
AVERAGE TEMPERATURE    (  K )   =   9.165E+01
```

t = 12000s

Table F-2

Global Quantities Printout, for whole LOX Tank - Case 1

(S.I. Units)

APPENDIX G

Global Parameters Printouts of Test Case 2

```
MASS  INFLOW RATE  (LBM/S)  =  3.064E+01
CALCULATED OUTFLOW (LBM/S)  = -4.644E+01
TOTAL MASS OF LOX  (LBM  )  =  5.151E+05
TOTAL LOX VOLUME   (FT**3)  =  7.251E+03     t = 2000 S
TOTAL MASS*ENTH    (BTU  )  =  3.415E+07
AVERAGE DENSITY (LBM/FT**3) =  7.104E+01
AVERAGE TEMPERATURE (  R )  =  1.633E+02


MASS  INFLOW RATE  (LBM/S)  =  3.063E+01
CALCULATED OUTFLOW (LBM/S)  = -3.897E+01
TOTAL MASS OF LOX  (LBM  )  =  4.933E+05
TOTAL LOX VOLUME   (FT**3)  =  6.950E+03     t = 4000 S
TOTAL MASS*ENTH    (BTU  )  =  3.279E+07
AVERAGE DENSITY (LBM/FT**3) =  7.098E+01
AVERAGE TEMPERATURE (  R )  =  1.637E+02


MASS  INFLOW RATE  (LBM/S)  =  3.062E+01
CALCULATED OUTFLOW (LBM/S)  = -3.957E+01
TOTAL MASS OF LOX  (LBM  )  =  4.715E+05
TOTAL LOX VOLUME   (FT**3)  =  6.649E+03
TOTAL MASS*ENTH    (BTU  )  =  3.142E+07     t = 6000 S
AVERAGE DENSITY (LBM/FT**3) =  7.092E+01
AVERAGE TEMPERATURE (  R )  =  1.640E+02


MASS  INFLOW RATE  (LBM/S)  =  3.061E+01
CALCULATED OUTFLOW (LBM/S)  = -3.955E+01
TOTAL MASS OF LOX  (LBM  )  =  4.498E+05
TOTAL LOX VOLUME   (FT**3)  =  6.348E+03     t = 8000 S
TOTAL MASS*ENTH    (BTU  )  =  3.004E+07
AVERAGE DENSITY (LBM/FT**3) =  7.086E+01
AVERAGE TEMPERATURE (  R )  =  1.644E+02


MASS  INFLOW RATE  (LBM/S)  =  3.060E+01
CALCULATED OUTFLOW (LBM/S)  = -3.961E+01
TOTAL MASS OF LOX  (LBM  )  =  4.282E+05     t = 10000 S
TOTAL LOX VOLUME   (FT**3)  =  6.047E+03
TOTAL MASS*ENTH    (BTU  )  =  2.866E+07
AVERAGE DENSITY (LBM/FT**3) =  7.080E+01
AVERAGE TEMPERATURE (  R )  =  1.647E+02
```

Table G-1

Global Quantities Printout for Half LOX Tank - Case 2

(British Units)

```
MASS  INFLOW RATE  (LBM/S)      =  3.059E+01
CALCULATED OUTFLOW (LBM/S)      = -3.983E+01
TOTAL MASS OF LOX  (LBM  )      =  4.066E+05     t = 12000 S
TOTAL LOX VOLUME   (FT**3)      =  5.747E+03
TOTAL MASS*ENTH    (BTU  )      =  2.727E+07
AVERAGE DENSITY (LBM/FT**3)     =  7.076E+01
AVERAGE TEMPERATURE (  R )      =  1.650E+02
```

```
MASS  INFLOW RATE  (LBM/S)      =  3.058E+01
CALCULATED OUTFLOW (LBM/S)      = -3.978E+01
TOTAL MASS OF LOX  (LBM  )      =  3.851E+05
TOTAL LOX VOLUME   (FT**3)      =  5.446E+03     t = 14000 S
TOTAL MASS*ENTH    (BTU  )      =  2.587E+07
AVERAGE DENSITY (LBM/FT**3)     =  7.071E+01
AVERAGE TEMPERATURE (  R )      =  1.653E+02
```

```
MASS  INFLOW RATE  (LBM/S)      =  3.057E+01
CALCULATED OUTFLOW (LBM/S)      = -3.941E+01
TOTAL MASS OF LOX  (LBM  )      =  3.550E+05
TOTAL LOX VOLUME   (FT**3)      =  5.025E+03     t = 16800 S
TOTAL MASS*ENTH    (BTU  )      =  2.390E+07
AVERAGE DENSITY (LBM/FT**3)     =  7.066E+01
AVERAGE TEMPERATURE (  R )      =  1.656E+02
```

```
MASS  INFLOW RATE  (LBM/S)      =  3.055E+01
CALCULATED OUTFLOW (LBM/S)      = -3.981E+01
TOTAL MASS OF LOX  (LBM  )      =  3.229E+05
TOTAL LOX VOLUME   (FT**3)      =  4.574E+03     t = 19800 S
TOTAL MASS*ENTH    (BTU  )      =  2.178E+07
AVERAGE DENSITY (LBM/FT**3)     =  7.061E+01
AVERAGE TEMPERATURE (  R )      =  1.658E+02
```

Table G-2

Global Quantities Printout for Half LOX Tank - Case 2

(British Units)

```
MASS  INFLOW  RATE   (KG/S) =  1.389E+01
CALCULATED OUTFLOW   (KG/S) = -2.106E+01
TOTAL MASS OF LOX    (KG  ) =  2.336E+05
TOTAL LOX VOLUME     (M**3) =  2.053E+02
TOTAL MASS*ENTH    (JOULES) =  3.600E+10
AVERAGE DENSITY (KG/M**3  ) =  1.138E+03
AVERAGE TEMPERATURE  (  K ) =  9.073E+01
```

t = 2000 S

```
MASS  INFLOW  RATE   (KG/S) =  1.389E+01
CALCULATED OUTFLOW   (KG/S) = -1.768E+01
TOTAL MASS OF LOX    (KG  ) =  2.237E+05
TOTAL LOX VOLUME     (M**3) =  1.968E+02
TOTAL MASS*ENTH    (JOULES) =  3.457E+10
AVERAGE DENSITY (KG/M**3  ) =  1.137E+03
AVERAGE TEMPERATURE  (  K ) =  9.094E+01
```

t = 4000 S

```
MASS  INFLOW  RATE   (KG/S) =  1.389E+01
CALCULATED OUTFLOW   (KG/S) = -1.795E+01
TOTAL MASS OF LOX    (KG  ) =  2.138E+05
TOTAL LOX VOLUME     (M**3) =  1.883E+02
TOTAL MASS*ENTH    (JOULES) =  3.312E+10
AVERAGE DENSITY (KG/M**3  ) =  1.136E+03
AVERAGE TEMPERATURE  (  K ) =  9.114E+01
```

t = 6000 S

```
MASS  INFLOW  RATE   (KG/S) =  1.388E+01
CALCULATED OUTFLOW   (KG/S) = -1.793E+01
TOTAL MASS OF LOX    (KG  ) =  2.040E+05
TOTAL LOX VOLUME     (M**3) =  1.798E+02
TOTAL MASS*ENTH    (JOULES) =  3.167E+10
AVERAGE DENSITY (KG/M**3  ) =  1.135E+03
AVERAGE TEMPERATURE  (  K ) =  9.133E+01
```

t = 8000 S

```
MASS  INFLOW  RATE   (KG/S) =  1.388E+01
CALCULATED OUTFLOW   (KG/S) = -1.796E+01
TOTAL MASS OF LOX    (KG  ) =  1.942E+05
TOTAL LOX VOLUME     (M**3) =  1.712E+02
TOTAL MASS*ENTH    (JOULES) =  3.021E+10
AVERAGE DENSITY (KG/M**3  ) =  1.134E+03
AVERAGE TEMPERATURE  (  K ) =  9.150E+01
```

t = 10000 S

Table G-3

Global Quantities Printout for Half LOX Tank - Case 2

MASS INFLOW RATE	(KG/S)	=	1.387E+01	
CALCULATED OUTFLOW	(KG/S)	=	-1.806E+01	
TOTAL MASS OF LOX	(KG)	=	1.844E+05	
TOTAL LOX VOLUME	(M**3)	=	1.627E+02	
TOTAL MASS*ENTH	(JOULES)	=	2.875E+10	t = 12000 S
AVERAGE DENSITY	(KG/M**3)	=	1.133E+03	
AVERAGE TEMPERATURE	(K)	=	9.166E+01	

MASS INFLOW RATE	(KG/S)	=	1.387E+01	
CALCULATED OUTFLOW	(KG/S)	=	-1.804E+01	
TOTAL MASS OF LOX	(KG)	=	1.746E+05	
TOTAL LOX VOLUME	(M**3)	=	1.542E+02	
TOTAL MASS*ENTH	(JOULES)	=	2.727E+10	
AVERAGE DENSITY	(KG/M**3)	=	1.132E+03	t = 14000 S
AVERAGE TEMPERATURE	(K)	=	9.181E+01	

MASS INFLOW RATE	(KG/S)	=	1.386E+01	
CALCULATED OUTFLOW	(KG/S)	=	-1.787E+01	
TOTAL MASS OF LOX	(KG)	=	1.610E+05	
TOTAL LOX VOLUME	(M**3)	=	1.423E+02	t = 16800 S
TOTAL MASS*ENTH	(JOULES)	=	2.520E+10	
AVERAGE DENSITY	(KG/M**3)	=	1.132E+03	
AVERAGE TEMPERATURE	(K)	=	9.197E+01	

MASS INFLOW RATE	(KG/S)	=	1.386E+01	
CALCULATED OUTFLOW	(KG/S)	=	-1.805E+01	
TOTAL MASS OF LOX	(KG)	=	1.465E+05	
TOTAL LOX VOLUME	(M**3)	=	1.295E+02	t = 19800 S
TOTAL MASS*ENTH	(JOULES)	=	2.296E+10	
AVERAGE DENSITY	(KG/M**3)	=	1.131E+03	
AVERAGE TEMPERATURE	(K)	=	9.213E+01	

Table G-4

Global Quantities Printout for Half LOX Tank - Case 2

(S.I. Units)

APPENDIX H

Global Parameters Printouts, for Test Case 3

MASS INFLOW RATE	(LBM/S)	= 3.0638E+01	
CALCULATED OUTFLOW	(LBM/S)	= -4.6253E+01	
TOTAL MASS OF LOX	(LBM)	= 5.1526E+05	
TOTAL LOX VOLUME	(FT**3)	= 7.2506E+03	t = 2000 S
TOTAL MASS*ENTH	(BTU)	= 3.4134E+07	
AVERAGE DENSITY	(LBM/FT**3)	= 7.1064E+01	
AVERAGE TEMPERATURE	(R)	= 1.6319E+02	

MASS INFLOW RATE	(LBM/S)	= 3.0628E+01	
CALCULATED OUTFLOW	(LBM/S)	= -4.1121E+01	
TOTAL MASS OF LOX	(LBM)	= 4.9355E+05	
TOTAL LOX VOLUME	(FT**3)	= 6.9498E+03	t = 4000 S
TOTAL MASS*ENTH	(BTU)	= 3.2758E+07	
AVERAGE DENSITY	(LBM/FT**3)	= 7.1017E+01	
AVERAGE TEMPERATURE	(R)	= 1.6346E+02	

MASS INFLOW RATE	(LBM/S)	= 3.0618E+01	
CALCULATED OUTFLOW	(LBM/S)	= -3.9719E+01	t = 6000 S
TOTAL MASS OF LOX	(LBM)	= 4.7187E+05	
TOTAL LOX VOLUME	(FT**3)	= 6.6490E+03	
TOTAL MASS*ENTH	(BTU)	= 3.1380E+07	
AVERAGE DENSITY	(LBM/FT**3)	= 7.0968E+01	
AVERAGE TEMPERATURE	(R)	= 1.6375E+02	

MASS INFLOW RATE	(LBM/S)	= 3.0608E+01	
CALCULATED OUTFLOW	(LBM/S)	= -3.9866E+01	
TOTAL MASS OF LOX	(LBM)	= 4.5020E+05	
TOTAL LOX VOLUME	(FT**3)	= 6.3482E+03	t = 8000 S
TOTAL MASS*ENTH	(BTU)	= 2.9999E+07	
AVERAGE DENSITY	(LBM/FT**3)	= 7.0918E+01	
AVERAGE TEMPERATURE	(R)	= 1.6404E+02	

MASS INFLOW RATE	(LBM/S)	= 3.0598E+01	
CALCULATED OUTFLOW	(LBM/S)	= -3.9806E+01	
TOTAL MASS OF LOX	(LBM)	= 4.2856E+05	
TOTAL LOX VOLUME	(FT**3)	= 6.0474E+03	t = 10000 S
TOTAL MASS*ENTH	(BTU)	= 2.8615E+07	
AVERAGE DENSITY	(LBM/FT**3)	= 7.0867E+01	
AVERAGE TEMPERATURE	(R)	= 1.6434E+02	

Table H-1

Global Quantities Printout for Half LOX Tank - Case 3

(British Units)

```
MASS  INFLOW RATE   (LBM/S)     =  3.0588E+01
CALCULATED OUTFLOW (LBM/S)     = -3.9832E+01
TOTAL MASS OF LOX  (LBM   )    =  4.0694E+05
TOTAL LOX VOLUME   (FT**3)     =  5.7466E+03     t = 12000 S
TOTAL MASS*ENTH    (BTU   )    =  2.7228E+07
AVERAGE DENSITY (LBM/FT**3)    =  7.0815E+01
AVERAGE TEMPERATURE (   R )    =  1.6464E+02

MASS  INFLOW RATE   (LBM/S)     =  3.0579E+01
CALCULATED OUTFLOW (LBM/S)     = -3.9654E+01
TOTAL MASS OF LOX  (LBM   )    =  3.8536E+05
TOTAL LOX VOLUME   (FT**3)     =  5.4458E+03     t = 14000 S
TOTAL MASS*ENTH    (BTU   )    =  2.5837E+07
AVERAGE DENSITY (LBM/FT**3)    =  7.0763E+01
AVERAGE TEMPERATURE (   R )    =  1.6494E+02

MASS  INFLOW RATE   (LBM/S)     =  3.0569E+01
CALCULATED OUTFLOW (LBM/S)     = -3.9617E+01
TOTAL MASS OF LOX  (LBM   )    =  3.6332E+05
TOTAL LOX VOLUME   (FT**3)     =  5.1450E+03     t = 16000 S
TOTAL MASS*ENTH    (BTU   )    =  2.4442E+07
AVERAGE DENSITY (LBM/FT**3)    =  7.0712E+01
AVERAGE TEMPERATURE (   R )    =  1.6524E+02

MASS  INFLOW RATE   (LBM/S)     =  3.0559E+01
CALCULATED OUTFLOW (LBM/S)     = -3.9685E+01
TOTAL MASS OF LOX  (LBM   )    =  3.4230E+05
TOTAL LOX VOLUME   (FT**3)     =  4.8442E+03     t = 18000 S
TOTAL MASS*ENTH    (BTU   )    =  2.3043E+07
AVERAGE DENSITY (LBM/FT**3)    =  7.0662E+01
AVERAGE TEMPERATURE (   R )    =  1.6554E+02

MASS  INFLOW RATE   (LBM/S)     =  3.0550E+01
CALCULATED OUTFLOW (LBM/S)     = -4.0016E+01
TOTAL MASS OF LOX  (LBM   )    =  3.2295E+05
TOTAL LOX VOLUME   (FT**3)     =  4.5735E+03     t = 19800 S
TOTAL MASS*ENTH    (BTU   )    =  2.1782E+07
AVERAGE DENSITY (LBM/FT**3)    =  7.0613E+01
AVERAGE TEMPERATURE (   R )    =  1.6582E+02
```

Table H-2

Global Quantities Printout for Half LOX Tank - Case 3

(British Units)

MASS INFLOW RATE	(KG/S)	=	1.3895E+01	
CALCULATED OUTFLOW	(KG/S)	=	-2.0976E+01	
TOTAL MASS OF LOX	(KG)	=	2.3368E+05	
TOTAL LOX VOLUME	(M**3)	=	2.0531E+02	t = 2000 S
TOTAL MASS*ENTH	(JOULES)	=	3.5984E+10	
AVERAGE DENSITY	(KG/M**3)	=	1.1382E+03	
AVERAGE TEMPERATURE	(K)	=	9.0659E+01	

MASS INFLOW RATE	(KG/S)	=	1.3890E+01	
CALCULATED OUTFLOW	(KG/S)	=	-1.8649E+01	
TOTAL MASS OF LOX	(KG)	=	2.2383E+05	
TOTAL LOX VOLUME	(M**3)	=	1.9679E+02	t = 4000 S
TOTAL MASS*ENTH	(JOULES)	=	3.4533E+10	
AVERAGE DENSITY	(KG/M**3)	=	1.1374E+03	
AVERAGE TEMPERATURE	(K)	=	9.0813E+01	

MASS INFLOW RATE	(KG/S)	=	1.3886E+01	
CALCULATED OUTFLOW	(KG/S)	=	-1.8013E+01	
TOTAL MASS OF LOX	(KG)	=	2.1400E+05	
TOTAL LOX VOLUME	(M**3)	=	1.8828E+02	t = 6000 S
TOTAL MASS*ENTH	(JOULES)	=	3.3080E+10	
AVERAGE DENSITY	(KG/M**3)	=	1.1366E+03	
AVERAGE TEMPERATURE	(K)	=	9.0971E+01	

MASS INFLOW RATE	(KG/S)	=	1.3881E+01	
CALCULATED OUTFLOW	(KG/S)	=	-1.8080E+01	
TOTAL MASS OF LOX	(KG)	=	2.0417E+05	
TOTAL LOX VOLUME	(M**3)	=	1.7976E+02	t = 8000 S
TOTAL MASS*ENTH	(JOULES)	=	3.1624E+10	
AVERAGE DENSITY	(KG/M**3)	=	1.1358E+03	
AVERAGE TEMPERATURE	(K)	=	9.1133E+01	

MASS INFLOW RATE	(KG/S)	=	1.3877E+01	
CALCULATED OUTFLOW	(KG/S)	=	-1.8053E+01	
TOTAL MASS OF LOX	(KG)	=	1.9436E+05	
TOTAL LOX VOLUME	(M**3)	=	1.7124E+02	
TOTAL MASS*ENTH	(JOULES)	=	3.0165E+10	t = 10000 S
AVERAGE DENSITY	(KG/M**3)	=	1.1350E+03	
AVERAGE TEMPERATURE	(K)	=	9.1299E+01	

Table H-3

Global Quantities Printout for Half LOX Tank - Case 3

(S.I. Units)

MASS INFLOW RATE	(KG/S)	=	1,3872E+01	t = 12000 S
CALCULATED OUTFLOW	(KG/S)	=	-1,8064E+01	
TOTAL MASS OF LOX	(KG)	=	1,8456E+05	
TOTAL LOX VOLUME	(M**3)	=	1,6272E+02	
TOTAL MASS*ENTH	(JOULES)	=	2,8703E+10	
AVERAGE DENSITY	(KG/M**3)	=	1,1342E+03	
AVERAGE TEMPERATURE	(K)	=	9,1468E+01	
MASS INFLOW RATE	(KG/S)	=	1,3868E+01	t = 14000 S
CALCULATED OUTFLOW	(KG/S)	=	-1,7984E+01	
TOTAL MASS OF LOX	(KG)	=	1,7477E+05	
TOTAL LOX VOLUME	(M**3)	=	1,5421E+02	
TOTAL MASS*ENTH	(JOULES)	=	2,7237E+10	
AVERAGE DENSITY	(KG/M**3)	=	1,1333E+03	
AVERAGE TEMPERATURE	(K)	=	9,1635E+01	
MASS INFLOW RATE	(KG/S)	=	1,3863E+01	t = 16000 S
CALCULATED OUTFLOW	(KG/S)	=	-1,7967E+01	
TOTAL MASS OF LOX	(KG)	=	1,6500E+05	
TOTAL LOX VOLUME	(M**3)	=	1,4569E+02	
TOTAL MASS*ENTH	(JOULES)	=	2,5766E+10	
AVERAGE DENSITY	(KG/M**3)	=	1,1325E+03	
AVERAGE TEMPERATURE	(K)	=	9,1800E+01	
MASS INFLOW RATE	(KG/S)	=	1,3859E+01	t = 18000 S
CALCULATED OUTFLOW	(KG/S)	=	-1,7998E+01	
TOTAL MASS OF LOX	(KG)	=	1,5524E+05	
TOTAL LOX VOLUME	(M**3)	=	1,3717E+02	
TOTAL MASS*ENTH	(JOULES)	=	2,4292E+10	
AVERAGE DENSITY	(KG/M**3)	=	1,1317E+03	
AVERAGE TEMPERATURE	(K)	=	9,1969E+01	
MASS INFLOW RATE	(KG/S)	=	1,[illegible]855E+01	t = 19800 S
CALCULATED OUTFLOW	(KG/S)	=	-1,[illegible]148E+01	
TOTAL MASS OF LOX	(KG)	=	1,4646E+05	
TOTAL LOX VOLUME	(M**3)	=	1,2951E+02	
TOTAL MASS*ENTH	(JOULES)	=	2,2962E+10	
AVERAGE DENSITY	(KG/M**3)	=	1,1309E+03	
AVERAGE TEMPERATURE	(K)	=	9,2121E+01	

Table H-4

Global Quantities Printout for Half LOX Tank - Case 3

(S.I. Units)

APPENDIX I

Global Parameters Printouts of Test Case 4

```
MASS  INFLOW RATE  (LBM/S)      =  3.0638E+01
CALCULATED OUTFLOW (LBM/S)      = -4.5695E+01
TOTAL MASS OF LOX  (LBM  )      =  3.4354E+05
TOTAL LOX VOLUME   (FT**3)      =  4.8357E+03
TOTAL MASS*ENTH    (BTU  )      =  2.2779E+07
AVERAGE DENSITY (LBM/FT**3)     =  7.1043E+01
AVERAGE TEMPERATURE (  R  )     =  1.6332E+02
```

t = 2000 S

```
MASS  INFLOW RATE  (LBM/S)      =  3.0628E+01
CALCULATED OUTFLOW (LBM/S)      = -4.1686E+01
TOTAL MASS OF LOX  (LBM  )      =  3.2186E+05
TOTAL LOX VOLUME   (FT**3)      =  4.5349E+03
TOTAL MASS*ENTH    (BTU  )      =  2.1400E+07
AVERAGE DENSITY (LBM/FT**3)     =  7.0973E+01
AVERAGE TEMPERATURE (  R  )     =  1.6372E+02
```

t = 4000 S

```
MASS  INFLOW RATE  (LBM/S)      =  3.0618E+01
CALCULATED OUTFLOW (LBM/S)      = -3.9756E+01
TOTAL MASS OF LOX  (LBM  )      =  3.0021E+05
TOTAL LOX VOLUME   (FT**3)      =  4.2341E+03
TOTAL MASS*ENTH    (BTU  )      =  2.0017E+07
AVERAGE DENSITY (LBM/FT**3)     =  7.0902E+01
AVERAGE TEMPERATURE (  R  )     =  1.6413E+02
```

t = 6000 S

```
MASS  INFLOW RATE  (LBM/S)      =  3.0608E+01
CALCULATED OUTFLOW (LBM/S)      = -3.9861E+01
TOTAL MASS OF LOX  (LBM  )      =  2.7860E+05
TOTAL LOX VOLUME   (FT**3)      =  3.9334E+03
TOTAL MASS*ENTH    (BTU  )      =  1.8630E+07
AVERAGE DENSITY (LBM/FT**3)     =  7.0830E+01
AVERAGE TEMPERATURE (  R  )     =  1.6455E+02
```

t = 8000 S

```
MASS  INFLOW RATE  (LBM/S)      =  3.0598E+01
CALCULATED OUTFLOW (LBM/S)      = -3.9946E+01
TOTAL MASS OF LOX  (LBM  )      =  2.5704E+05
TOTAL LOX VOLUME   (FT**3)      =  3.6326E+03
TOTAL MASS*ENTH    (BTU  )      =  1.7236E+07
AVERAGE DENSITY (LBM/FT**3)     =  7.0760E+01
AVERAGE TEMPERATURE (  R  )     =  1.6496E+02
```

t = 10000 S

Table I-1

Global Quantities Printout for Half LOX Tank - Case 4

(British Units)

```
MASS  INFLOW RATE   (LBM/S)   =   3.0588E+01
CALCULATED OUTFLOW (LBM/S)   =  -4.0072E+01
TOTAL MASS OF LOX   (LBM   )  =   2.3553E+05
TOTAL LOX VOLUME    (FT**3)   =   3.3318E+03      t = 12000 S
TOTAL MASS*ENTH     (BTU   )  =   1.5837E+07
AVERAGE DENSITY (LBM/FT**3)   =   7.0691E+01
AVERAGE TEMPERATURE (   R )   =   1.6537E+02

MASS  INFLOW RATE   (LBM/S)   =   3.0579E+01
CALCULATED OUTFLOW (LBM/S)   =  -4.0190E+01
TOTAL MASS OF LOX   (LBM   )  =   2.1405E+05
TOTAL LOX VOLUME    (FT**3)   =   3.0310E+03      t = 14000 S
TOTAL MASS*ENTH     (BTU   )  =   1.4433E+07
AVERAGE DENSITY (LBM/FT**3)   =   7.0620E+01
AVERAGE TEMPERATURE (   R )   =   1.6578E+02

MASS  INFLOW RATE   (LBM/S)   =   3.0569E+01
CALCULATED OUTFLOW (LBM/S)   =  -4.0300E+01
TOTAL MASS OF LOX   (LBM   )  =   1.9260E+05
TOTAL LOX VOLUME    (FT**3)   =   2.7302E+03      t = 16000 S
TOTAL MASS*ENTH     (BTU   )  =   1.3025E+07
AVERAGE DENSITY (LBM/FT**3)   =   7.0544E+01
AVERAGE TEMPERATURE (   R )   =   1.6622E+02

MASS  INFLOW RATE   (LBM/S)   =   3.0559E+01
CALCULATED OUTFLOW (LBM/S)   =  -4.0435E+01
TOTAL MASS OF LOX   (LBM   )  =   1.7118E+05
TOTAL LOX VOLUME    (FT**3)   =   2.4295E+03      t = 18000 S
TOTAL MASS*ENTH     (BTU   )  =   1.1615E+07
AVERAGE DENSITY (LBM/FT**3)   =   7.0460E+01
AVERAGE TEMPERATURE (   R )   =   1.6671E+02

MASS  INFLOW RATE   (LBM/S)   =   3.055[illegible]E+01
CALCULATED OUTFLOW (LBM/S)   =  -4.0609E+01
TOTAL MASS OF LOX   (LBM   )  =   1.5191E+05
TOTAL LOX VOLUME    (FT**3)   =   2.1587E+03      t = 19800 S
TOTAL MASS*ENTH     (BTU   )  =   1.0343E+07
AVERAGE DENSITY (LBM/FT**3)   =   7.0372E+01
AVERAGE TEMPERATURE (   R )   =   1.6722E+02
```

Table I-2

Global Quantities Printout for Half LOX Tank - Case 4

(British Units)

```
MASS  INFLOW  RATE      (KG/S) =  1.3895E+01
CALCULATED OUTFLOW      (KG/S) = -2.0723E+01
TOTAL MASS OF LUX       (KG   ) =  1.5580E+05      t = 2000 S
TOTAL LOX VOLUME        (M**3) =  1.3693E+02
TOTAL MASS*ENTH      (JOULES) =  2.4013E+10
AVERAGE DENSITY (KG/M**3   ) =  1.1378E+03
AVERAGE TEMPERATURE   (  K ) =  9.0732E+01

MASS  INFLOW  RATE      (KG/S) =  1.3890E+01
CALCULATED OUTFLOW      (KG/S) = -1.8905E+01
TOTAL MASS OF LUX       (KG   ) =  1.4597E+05
TOTAL LUX VOLUME        (M**3) =  1.2841E+02      t = 4000 S
TOTAL MASS*ENTH      (JOULES) =  2.2560E+10
AVERAGE DENSITY (KG/M**3   ) =  1.1367E+03
AVERAGE TEMPERATURE   (  K ) =  9.0957E+01

MASS  INFLOW  RATE      (KG/S) =  1.3886E+01
CALCULATED OUTFLOW      (KG/S) = -1.8030E+01
TOTAL MASS OF LUX       (KG   ) =  1.3615E+05
TOTAL LOX VOLUME        (M**3) =  1.1990E+02      t = 6000 S
TOTAL MASS*ENTH      (JOULES) =  2.1102E+10
AVERAGE DENSITY (KG/M**3   ) =  1.1356E+03
AVERAGE TEMPERATURE   (  K ) =  9.1186E+01

MASS  INFLOW  RATE      (KG/S) =  1.3881E+01
CALCULATED OUTFLOW      (KG/S) = -1.8078E+01
TOTAL MASS OF LOX       (KG   ) =  1.2635E+05
TOTAL LOX VOLUME        (M**3) =  1.1138E+02      t = 8000 S
TOTAL MASS*ENTH      (JOULES) =  1.9639E+10
AVERAGE DENSITY (KG/M**3   ) =  1.1344E+03
AVERAGE TEMPERATURE   (  K ) =  9.1417E+01

MASS  INFLOW  RATE      (KG/S) =  1.3877E+01
CALCULATED OUTFLOW      (KG/S) = -1.8116E+01
TOTAL MASS OF LUX       (KG   ) =  1.1657E+05
TOTAL LUX VOLUME        (M**3) =  1.0286E+02      t = 10000 S
TOTAL MASS*ENTH      (JOULES) =  1.8170E+10
AVERAGE DENSITY (KG/M**3   ) =  1.1333E+03
AVERAGE TEMPERATURE   (  K ) =  9.1647E+01
```

Table I-3

Global Quantities Printout for Half LOX Tank - Case 4

(S.I. Units)

```
MASS  INFLOW  RATE     (KG/S) =  1.3872E+01
CALCULATED OUTFLOW     (KG/S) = -1.8173E+01
TOTAL MASS OF LOX      (KG  ) =  1.0682E+05
TOTAL LOX VOLUME       (M**3) =  9.4345E+01      t = 12000 S
TOTAL MASS*ENTH      (JOULES) =  1.6695E+10
AVERAGE DENSITY (KG/M**3    ) =  1.1322E+03
AVERAGE TEMPERATURE  (  K   ) =  9.1870E+01

MASS  INFLOW  RATE     (KG/S) =  1.3868E+01
CALCULATED OUTFLOW     (KG/S) = -1.8227E+01
TOTAL MASS OF LOX      (KG  ) =  9.7074E+04
TOTAL LOX VOLUME       (M**3) =  8.5828E+01      t = 14000 S
TOTAL MASS*ENTH      (JOULES) =  1.5215E+10
AVERAGE DENSITY (KG/M**3    ) =  1.1310E+03
AVERAGE TEMPERATURE  (  K   ) =  9.2099E+01

MASS  INFLOW  RATE     (KG/S) =  1.3863E+01
CALCULATED OUTFLOW     (KG/S) = -1.8277E+01
TOTAL MASS OF LOX      (KG  ) =  8.7348E+04
TOTAL LOX VOLUME       (M**3) =  7.7311E+01      t = 16000 S
TOTAL MASS*ENTH      (JOULES) =  1.3731E+10
AVERAGE DENSITY (KG/M**3    ) =  1.1298E+03
AVERAGE TEMPERATURE  (  K   ) =  9.2342E+01

MASS  INFLOW  RATE     (KG/S) =  1.3859E+01
CALCULATED OUTFLOW     (KG/S) = -1.8338E+01
TOTAL MASS OF LOX      (KG  ) =  7.7632E+04
TOTAL LOX VOLUME       (M**3) =  6.8794E+01      t = 18000 S
TOTAL MASS*ENTH      (JOULES) =  1.2244E+10
AVERAGE DENSITY (KG/M**3    ) =  1.1285E+03
AVERAGE TEMPERATURE  (  K   ) =  9.2616E+01

MASS  INFLOW  RATE     (KG/S) =  1.3855E+01
CALCULATED OUTFLOW     (KG/S) = -1.8417E+01
TOTAL MASS OF LOX      (KG  ) =  6.8896E+04
TOTAL LOX VOLUME       (M**3) =  6.1128E+01      t = 19800 S
TOTAL MASS*ENTH      (JOULES) =  1.0904E+10
AVERAGE DENSITY (KG/M**3    ) =  1.1271E+03
AVERAGE TEMPERATURE  (  K   ) =  9.2900E+01
```

Table I-4

Global Quantities Printout for Half LOX Tank - Case 4

(S.I. Units)